

A study of SUSY signatures at the Tevatron in models with near mass degeneracy of the lightest chargino and neutralino

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Abstract

For some choices of soft SUSY-breaking parameters, the LSP is a stable neutralino $\tilde{\chi}_1^0$, the NLSP is a chargino $\tilde{\chi}_1^\pm$ almost degenerate in mass with the LSP ($\Delta m_{\tilde{\chi}_1} \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \sim m_\pi$ —few GeV), and all other sparticles are relatively heavy. In this case, detection of sparticles in the usual, mSUGRA-motivated signals will be difficult, since the decay products in $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \dots$ will be very soft, and alternative signals must be considered. Here, we study the viability of signatures at the Tevatron based on highly-ionizing charged tracks, disappearing charged tracks, large impact parameters, missing transverse energy and a jet or a photon, and determine the mass reach of such signatures assuming that only the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are light. We also consider the jet+ \cancel{E}_T and $\gamma + \cancel{E}_T$ signatures assuming that the gluino is also light with $m_{\tilde{g}} \sim m_{\tilde{\chi}_1^\pm}$. We find that the mass reach is critically dependent upon $\Delta m_{\tilde{\chi}_1}$ and $m_{\tilde{g}} - m_{\tilde{\chi}_1^\pm}$. If $\Delta m_{\tilde{\chi}_1}$ is sufficiently big that $c\tau(\tilde{\chi}_1^\pm) \lesssim \text{few cm}$ and $m_{\tilde{g}}$ is large, there is a significant possibility that the limits on $m_{\tilde{\chi}_1^\pm}$ based on LEP2 data cannot be extended at the Tevatron. If $c\tau(\tilde{\chi}_1^\pm) > \text{few cm}$, relatively background-free signals exist that will give a clear signal of $\tilde{\chi}_1^\pm$ production (for some range of $m_{\tilde{\chi}_1^\pm}$) even if $m_{\tilde{g}}$ is very large.

1 Introduction

In mSUGRA models, the soft SUSY-breaking parameters for the gauginos satisfy a common boundary condition at the GUT scale, leading to a relatively large mass splitting between the lightest chargino and the lightest neutralino (most often the LSP). However, for different boundary conditions, this need not be the case, and discovering SUSY may be more challenging or, at least, more difficult to fully interpret. Here, we focus on the possibility that the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are very degenerate in mass. This arises naturally in two scenarios.

1. $M_2 < M_1 \ll |\mu|$: As reviewed in Ref. [1], this hierarchy occurs when the gaugino masses are dominated by or entirely generated by loop corrections. Models of this type include the O-II

superstring model [2, 3, 4, 5] and the closely related models in which SUSY-breaking arises entirely from the conformal anomaly [6, 7]. The same hierarchy also occurs when SUSY is broken by an F -term that is not an $SU(5)$ singlet but is rather a member of the **200** representation contained in $(\mathbf{24} \times \mathbf{24})_{\text{symmetric}} = \mathbf{1} \oplus \mathbf{24} \oplus \mathbf{75} \oplus \mathbf{200}$ [8].

It is demonstrative to give some specific results for the gaugino mass parameters at the scale M_U (m_Z). The O-II model with $\delta_{GS} = -4$ yields $M_3 : M_2 : M_1 = 1 : 5 : 10.6$ (6 : 10 : 10.6), the O-II model with $\delta_{GS} = 0$ (equivalent to the simplest version of the conformal anomaly approach) yields $M_3 : M_2 : M_1 = 3 : 1 : 33/5$ (3 : 0.3 : 1), while the **200** model yields 1 : 2 : 10 (6 : 4 : 10). As a result:

- In the **200** model and the O-II $\delta_{GS} = 0$ (or pure conformal anomaly) model, M_2 is substantially below M_1 and $\Delta m_{\tilde{\chi}_1} \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ can be very small.
 - In the O-II $\delta_{GS} = -4$ case, M_2 is only slightly less than M_1 at low energies, but still $\Delta m_{\tilde{\chi}_1} < 1$ GeV is very typical and $\Delta m_{\tilde{\chi}_1} < 1$ GeV if $|\mu| \gtrsim 1$ TeV or if $\tan \beta$ is not large and RGE electroweak symmetry breaking is imposed [4].
 - In the **200** model, and especially the O-II $\delta_{GS} = -4$ model, both $m_{\tilde{\chi}_2^0}$ and $m_{\tilde{g}}$ are typically quite close to the common $\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ mass, and it is natural for the squark and slepton masses to be much heavier than any of the gaugino masses. Typical values of $|\mu|$ required by RGE electroweak symmetry breaking are large, implying that the higgsino $\tilde{\chi}_2^\pm, \tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$ states are very heavy.
 - In the O-II $\delta_{GS} = 0$ (or conformal anomaly) model, the gluino is typically very heavy compared to the chargino.
2. $|\mu| \ll M_{1,2}$: In this case, the $\tilde{\chi}_1^\pm$, the $\tilde{\chi}_1^0$ and the $\tilde{\chi}_2^0$ are all closely degenerate and higgsino-like, while the gaugino states are much heavier. Extreme degeneracy, $\Delta m_{\tilde{\chi}_1} < 1$ GeV, is only achieved for $M_{1,2} \gtrsim 5$ TeV. The squark and slepton masses might also be large. Since currently there is less motivation for this scenario, we will only make occasional remarks regarding it.

The neutralino and chargino couplings to W and Z bosons take the form $ig\gamma^\mu[G_L P_L + G_R P_R]$, where $P_L = (1 - \gamma_5)/2$ and $P_R = (1 + \gamma_5)/2$. Ignoring CP violation, G_L and G_R are [9]:

$$W^+ \rightarrow \tilde{\chi}_i^+ \tilde{\chi}_j^0 : \quad G_L = -\frac{1}{\sqrt{2}}V_{i2}N_{j4} + V_{i1}N_{j2}, \quad G_R = +\frac{1}{\sqrt{2}}U_{i2}N_{j3} + U_{i1}N_{j2}, \quad (1)$$

$$Z \rightarrow \tilde{\chi}_i^+ \tilde{\chi}_j^- : \quad G_L = V_{i1}V_{j1} + \frac{1}{2}V_{i2}V_{j2}, \quad G_R = U_{i1}U_{j1} + \frac{1}{2}U_{i2}U_{j2}, \quad (2)$$

$$Z \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0 : \quad G_R = -G_L = \frac{1}{2}(N_{i3}N_{j3} - N_{i4}N_{j4}), \quad (3)$$

where the V, U matrices diagonalize the chargino mass matrix (with 1, 2 referring to the $\widetilde{W}^\pm, \widetilde{H}^\pm$ basis) and N diagonalizes the neutralino mass matrix (with 1, 2, 3, 4 referring to the $\widetilde{B}, \widetilde{W}^0, \widetilde{H}_1^0, \widetilde{H}_2^0$ basis). From these expressions we learn the following.

1. When $M_2 < M_1 \ll |\mu|$, one finds $V_{11}, U_{11} \sim 1$, $V_{12}, U_{12} \sim 0$, $N_{11}, N_{13}, N_{14}, N_{22}, N_{23}, N_{24} \sim 0$, and $N_{12}, N_{21} \sim 1$. Focusing on the lighter $\widetilde{\chi}_1^\pm, \widetilde{\chi}_1^0$ and $\widetilde{\chi}_2^0$ states, the $Z \rightarrow \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$, $Z \rightarrow \widetilde{\chi}_1^0 \widetilde{\chi}_2^0$, $Z \rightarrow \widetilde{\chi}_2^0 \widetilde{\chi}_2^0$, and $W^\pm \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_2^0$ cross sections are all small, while $Z, \gamma \rightarrow \widetilde{\chi}_1^+ \widetilde{\chi}_1^-$ and $W^\pm \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_1^0$ can have large rates.
2. When $|\mu| \ll M_{1,2}$, one has: $V_{11}, U_{11} \sim 0$, $V_{12}, U_{12} \sim \text{sgn}(\mu), 1$; $N_{11}, N_{12}, N_{21}, N_{22} \sim 0$, $N_{13} = N_{14} = N_{23} = -N_{24} = 1/\sqrt{2}$. In this case, the $Z, \gamma \rightarrow \widetilde{\chi}_1^+ \widetilde{\chi}_1^-$, $Z \rightarrow \widetilde{\chi}_1^0 \widetilde{\chi}_2^0$, $W^\pm \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_1^0$, and $W^\pm \rightarrow \widetilde{\chi}_1^\pm \widetilde{\chi}_2^0$ rates will be large [but smaller than the unsuppressed channel rates in scenario (1)] and $Z \rightarrow \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$, $Z \rightarrow \widetilde{\chi}_2^0 \widetilde{\chi}_2^0$ are suppressed.

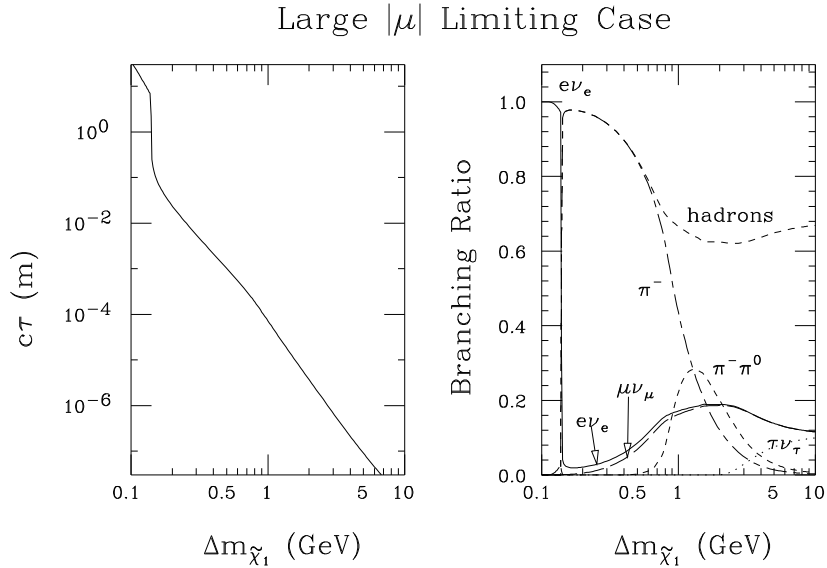


Figure 1: The $c\tau$ and branching ratios for $\widetilde{\chi}_1^-$ decay as a function of $\Delta m_{\widetilde{\chi}_1} \equiv m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0}$ for the $M_2 < M_1 \ll |\mu|$ scenario. From Ref. [5].

The most critical ingredients in the phenomenology of such models are the lifetime and the decay modes of the $\widetilde{\chi}_1^\pm$, which in turn depend almost entirely on $\Delta m_{\widetilde{\chi}_1}$ when the latter is small. The $c\tau$ and branching ratios of the $\widetilde{\chi}_1^\pm$ as a function of $\Delta m_{\widetilde{\chi}_1}$ have been computed in Ref. [5] (see also the closely related computation for a nearly degenerate heavy lepton pair L^\pm, L^0 in Ref. [10]) and are illustrated in Fig. 1 for scenario (1). For $\Delta m_{\widetilde{\chi}_1} < m_\pi$, only $\widetilde{\chi}_1^\pm \rightarrow e^\pm \nu_e \widetilde{\chi}_1^0$ is important and $c\tau > 10$ m. Once $\Delta m_{\widetilde{\chi}_1} > m_\pi$, the $\widetilde{\chi}_1^\pm \rightarrow \pi^\pm \widetilde{\chi}_1^0$ mode turns on and is dominant for $\Delta m_{\widetilde{\chi}_1} \lesssim 800$ MeV, at which point the

multi-pion modes start to become important: correspondingly, one finds $c\tau \lesssim 10 - 20$ cm for $\Delta m_{\tilde{\chi}_1}$ just above m_π decreasing to $c\tau \sim 100 \mu\text{m}$ by $\Delta m_{\tilde{\chi}_1} \sim 1$ GeV. In general, the exact value of $\Delta m_{\tilde{\chi}_1}$ is model dependent. However, it is generally true that $\Delta m_{\tilde{\chi}_1} < m_\pi$ is difficult to achieve. Even in scenario (1), where the tree-level mass splitting can be extremely small, the electroweak radiative corrections [11] increase the mass splitting significantly; one finds (see e.g. the $\Delta m_{\tilde{\chi}_1}$ graphs in [4]) that $\Delta m_{\tilde{\chi}_1} < m_\pi$ is only possible for very special parameter choices. Most typically $\Delta m_{\tilde{\chi}_1}$ is predicted to lie in the range from slightly above m_π to several GeV. As noted earlier, the tree-level value of $\Delta m_{\tilde{\chi}_1}$ in scenario (2) is normally substantially larger than m_π , and the one-loop corrections do not have much influence on the phenomenology. For later reference, we present in Table 1 the specific $c\tau$ values as a function of $\Delta m_{\tilde{\chi}_1}$ that we have employed in our Monte Carlo studies.

| | | | | | | | |
|---|-------|-------|-------|-------|-------|--------|--------|
| $\Delta m_{\tilde{\chi}_1} (\text{ MeV})$ | 125 | 130 | 135 | 138 | 140 | 142.5 | 150 |
| $c\tau(\text{cm})$ | 1155 | 918.4 | 754.1 | 671.5 | 317.2 | 23.97 | 10.89 |
| $\Delta m_{\tilde{\chi}_1} (\text{ MeV})$ | 160 | 180 | 185 | 200 | 250 | 300 | 500 |
| $c\tau(\text{cm})$ | 6.865 | 3.719 | 3.291 | 2.381 | 1.042 | 0.5561 | 0.1023 |

Table 1: Summary of $c\tau$ values as a function of $\Delta m_{\tilde{\chi}_1}$ as employed in Monte Carlo simulations.

In order to set the stage for later, detailed studies, let us temporarily assume that only the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are light and briefly preview the types of signals that will be important for different ranges of $\Delta m_{\tilde{\chi}_1}$. For this discussion, we ask the reader to imagine a canonical detector (e.g. CDF or DØ at RunII) with the following components ordered according to increasing radial distance from the beam.

- An inner silicon vertex (SVX) detector extending radially from the beam axis. The CDF RunII vertex detector has layers at $r \sim 1.6, 3, 4.5, 7, 8.5$ and 11 cm (the first and second layers are denoted L00 and L0, respectively) extending out to $z = \pm 45$ cm [12]. The DØ SVX has 4 layers (but 2 are double-sided), with the first at 2.5 cm and the last at 11 cm.
- A central tracker (CT) extending from 15 cm to 73 cm (DØ) or from roughly 20 cm to 130 cm (CDF).
- A thin pre-shower layer (PS).
- An electromagnetic calorimeter (EC) and hadronic calorimeter (HC).
- The inner-most muon chambers (MC), starting just beyond the HC. The DØ inner central muon chambers form (very roughly) a box, the ends of which (through which the beam passes) are a

5.4 m \times 5.4 m square and the sides of which are 8 m in length. The sides (parallel to the beams) cover $|\eta| < 1$, while the ends are instrumented out to $|\eta| < 2$. The CDF inner muon chambers form roughly a barrel at a radial distance of 3.5 m with length of about 5 m. There is no muon detection capability on the ends of the barrel, so only $|\eta| < 0.6$ is covered by the inner chambers.

- Both CDF and DØ will have a precise time-of-flight measurement (TOF) for any charged particle that makes it to the muon chambers.

It is important to note that the SVX, CT and PS can all give (independent) measurements of the dE/dx from ionization of a track passing through them. This will be important to distinguish a heavily-ionizing chargino (which would be \geq twice minimal ionizing [2MIP] for $\beta\gamma \leq 0.85$) from an isolated minimally ionizing particle [1MIP]. For example, at DØ the rejection against isolated 1MIP tracks will be $\text{few} \times 10^{-3}$, $\text{few} \times 10^{-3}$, and $\sim 10^{-1}$ for tracks that pass through the SVX, CT and PS, respectively, with an efficiency of 90% for tracks with $\beta\gamma < 0.85$ [13].¹ At CDF, the discrimination factors have not been studied in detail but should be roughly similar [14]. Because of correlations, one cannot simply multiply these numbers together to get the combined discrimination power of the SVX, CT and PS for an isolated track that passes through all three; for such a track with $\beta\gamma < 0.85$, the net discrimination factor would probably be of order $\text{few} \times 10^{-5}$. A summary of our shorthand notations for detector components appears in Table 2. At LEP/LEP2, the detector structure is somewhat different and important features will be noted where relevant. We now list the possible signals.

| Component | Description |
|-----------|---|
| SVX | Silicon vertex detector from close to beam pipe to ~ 11 cm. |
| CT | Central tracker starting just past SVX. |
| PS | Pre-shower just outside the tracker. |
| EC | Electromagnetic calorimeter. |
| HC | Hadronic calorimeter. |
| TOF | Time-of-flight measurement after HC and just before MC. |
| MC | Muon chamber with first layer after the HC and just beyond the TOF. |

Table 2: Summary of detector components referred to in the text.

¹It is a combination of Landau fluctuations, electronic noise and, most importantly in hadron collisions, overlapping soft tracks that is responsible for these discrimination factors being worse than one might naively expect.

(a) LHIT and TOF signals:

For $\Delta m_{\tilde{\chi}_1} < m_\pi$, a heavy chargino produced in a collision travels a distance of order a meter or more and will often penetrate to the muon chambers. If it does, the chargino may be distinguished from a muon by heavy ionization in the SVX, CT and PS (e.g., if $\beta\gamma < 0.85$ the track will be at least 2MIP). There should be no hadronic energy deposits associated with this track, implying that the energy deposited in the hadronic calorimeter should be consistent with ionization energy losses for the measured β . With appropriate cuts, such a signal should be background-free. This type of long, heavily-ionizing track signal will be denoted as an LHIT signal.

If the chargino penetrates to the muon chambers, its large mass will also be evident from the time delay of its TOF signal. This delay can substitute for the heavy ionization requirement. The passage of the chargino through the muon chamber provides an adequate trigger for the events. In addition, the chargino will be clearly visible as an isolated track in the CT, and this track could also be used to trigger the event. In later analysis (off-line even), substantial momentum can be required for the track without loss of efficiency. (The typical transverse momentum of a chargino when pair-produced in hadronic collisions is of order 1/2 the mass.)

After a reasonable cut on p_T , the LHIT and TOF signals will be background free. In addition, we will find that if the chargino mass is near the upper limits that can be probed by the LHIT and TOF signals, the LHIT and TOF requirements can be simultaneously imposed without much loss of efficiency.

(b) DIT signals:

For $\Delta m_{\tilde{\chi}_1}$ above but near m_π , the chargino will often appear as an isolated track in the central tracker but it will decay before the muon chamber. (The appropriate mass range for which this has significant probability is $m_\pi < \Delta m_{\tilde{\chi}_1} < 145$ MeV, for which $c\tau \gtrsim 17$ cm.) As such a chargino passes part way through the calorimeters beyond the CT, it will deposit little energy. In particular, any energy deposit in the hadronic calorimeter should be no larger than that consistent with ionization energy deposits for the β of the track as measured using ionization information from the SVX+CT+PS. (In general, the chargino will only deposit ionization energy up to the point of its decay. Afterwards, the weakly-interacting neutralino will carry away most of the remaining energy, leaving only a very soft pion or lepton remnant.) Thus, we require that the track effectively disappear once it exits the CT. (The point at which the ionization energy deposits end would typically be observable in a calorimeter with sufficient radial segmentation, but we do not include this in our analysis.) Such a disappearing, isolated track will be called a DIT. The DIT will have substantial p_T , which can be used to trigger the event. A track with large p_T from a background process will either be a hadron, an electron or a muon. The first two will leave large deposits in the calorimeters (EC and/or HC) and the latter will penetrate to the muon chamber. Thus, the signal described is very possibly a background-free signal. If not, a

requirement of heavy ionization in the SVX, CT and PS will certainly eliminate backgrounds, but with some sacrifice of signal events.

We will also consider the possibility of requiring that the DIT track be heavily ionizing. In the most extreme case, we require that the average ionization measured in the SVX, CT and PS correspond to $\beta < 0.6$ ($\beta\gamma < 0.75$). For a DIT signal, this is a very strong cut once $\Delta m_{\tilde{\chi}_1}$ is large enough that the average $c\tau$ is smaller than the radius of the CT. This is because rather few events will have both large enough $\beta\gamma c\tau$ to pass all the way through the CT and small enough β to satisfy the heavy ionization requirement.

(c) STUB and KINK signals:

For $145 \text{ MeV} < \Delta m_{\tilde{\chi}_1} < 160 \text{ MeV}$, $17 \text{ cm} > c\tau > 7 \text{ cm}$. For such $c\tau$, the probability for the chargino to pass all the way through the central tracker will be small, but the chargino will be at least fairly likely to pass all the way through the SVX. An off-line analysis will find a track in the SVX that does not make it through the CT, and is certainly not associated with any calorimeter energy deposits. Such a short track we term a STUB. One may be able to detect the soft pion that is emitted by the decay of the STUB chargino. At a hadron collider, the primary difficulty associated with a STUB signal is that it will not provide its own Level-1 trigger. (At both CDF and DØ, information from the SVX can only be analyzed at Level-3 or later.) One must trigger the event by, for example, requiring missing transverse energy (\cancel{E}_T) above some appropriate value and/or extra jets in the event.

Once an interesting event is triggered, off-line analysis will provide a measurement of the ionization deposited by the STUB in the SVX. However, $\beta\gamma < 0.85$ (the 2MIP requirement) can conflict with the requirement that the chargino pass all the way through the SVX. For a given $c\tau$, the minimum β required for a $\tilde{\chi}_1^\pm$ with small $|\eta|$ to reach the final SVX layer at $r = 11 \text{ cm}$ is given by $\beta\gamma c\tau = 11 \text{ cm}$. In comparison, a chargino with $\Delta m_{\tilde{\chi}_1} = 160 \text{ MeV}$ has $c\tau = 7 \text{ cm}$ (on average) and $\beta \geq 0.85$ is typically required to reach 11 cm; the corresponding $\beta\gamma$ value would be substantially above 0.85 and the ionization level would be $\leq 2\text{MIP}$. For smaller $\Delta m_{\tilde{\chi}_1}$, the $c\tau$ of the chargino is larger and smaller β values will typically allow both $\beta\gamma < 0.85$ and $\beta\gamma c\tau > 11 \text{ cm}$. Of course, the actual decay time is characterized by an exponential distribution, so that for a given $\Delta m_{\tilde{\chi}_1}$ some charginos will reach 11 cm with substantially lower velocity than that needed on average. Similarly, charginos that decay ‘late’ can have a track that extends into the central tracker even for $\beta\gamma$ substantially below 0.85. Still, it would be better to find requirements that do not employ heavy ionization but still leave us with a background-free signal.

In particular, it might be possible to see (in the CT) the charged pion that emerges from the “disappearing” track seen as a STUB. In the rest frame of the chargino, the pion energy is given by $E_\pi^* \simeq \Delta m_{\tilde{\chi}_1}$ and $p_\pi^* \simeq \sqrt{\Delta m_{\tilde{\chi}_1}^2 - m_\pi^2}$. For $m_\pi \leq \Delta m_{\tilde{\chi}_1} \leq 160 \text{ MeV}$, one has $0 \leq p_\pi^* \leq 77 \text{ MeV}$, but there will be some boost of the pion in going to the laboratory frame. In this frame, the (transverse) radius

of curvature of the pion is $R(\text{cm}) = \frac{p_\pi^T(\text{MeV})}{3B(\text{T})}$. For the CDF detector, $B \sim 1.4 \text{ T}$ and $p_\pi^T \sim 77 \text{ MeV}$ yields $R \sim 18 \text{ cm}$. Thus, most of the soft pion tracks from charginos that decay after passing through the vertex detector will be seen in the tracker. Typically, the soft pion track that intersects the STUB track will do so at a large angle, a signature we call a KINK.

(d) HIP + KINK signals:

For $160 \text{ MeV} < \Delta m_{\tilde{\chi}_1} < 190 \text{ MeV}$, $7 \text{ cm} > c\tau > 3 \text{ cm}$. Some of the produced charginos will decay late compared to $c\tau$ and yield a STUB signature of the type discussed just above. More typically, however, the $\tilde{\chi}_1^\pm$ will pass through two to three layers of the SVX. The $\tilde{\chi}_1^\pm$ track will then end and turn into a single charged pion with substantially different momentum. Both the sudden disappearance of and the lack of any calorimeter energy deposits associated with the $\tilde{\chi}_1^\pm$ track will help to distinguish it from other light-particle tracks that would normally register in all layers of the SVX and in the calorimeters.

For $160 \text{ MeV} < \Delta m_{\tilde{\chi}_1} < 190 \text{ MeV}$, $p_\pi^* \sim 77 - 130 \text{ MeV}$. The corresponding transverse impact parameter resolution of the SVX, σ_b , is approximately $300 - 170 \mu\text{m}$ (taking $p_\pi^T \sim p_\pi^*$ and applying the 1σ values from Fig. 2.2 of [12] when L00 is included), and is much smaller than the typical impact parameter (which is a sizeable fraction of $\sim c\tau > 3 \text{ cm}$). Thus, we will consider a signal consisting of an appropriate trigger (we will use large missing transverse energy) and an isolated pion with high impact parameter (HIP) that forms a KINK with a short track in the SVX.

In the present study, we do not explicitly look for KINK's. This would require going beyond the transverse impact parameter and performing a three-dimensional reconstruction of the point at which the chargino decays and tracking the soft pion (and all other charged tracks) through the magnetic field. Nor do we attempt to include discrimination against backgrounds coming from ionization deposit measurements on the few SVX layers that the chargino does pass through. In other words, we only make use of the HIP signature in our estimates. Thus, sensitivity based on our HIP studies in this mass range will be overly conservative. Presumably, the actual experiments will do better.

(e) HIP signals:

For $\Delta m_{\tilde{\chi}_1} > 230 \text{ MeV}$, $c\tau < 1.6 \text{ cm}$ and the typical $\tilde{\chi}_1^\pm$ will not even pass through the innermost SVX layer unless β is very large. However, $p_\pi^* > 180 \text{ MeV}$ and the impact parameter resolution for the single emitted pion moves into the $< 150 \mu\text{m}$ range. For example, if $\Delta m_{\tilde{\chi}_1} = 240, 300, 500, 1000 \text{ MeV}$, $c\tau \sim 1.2, 0.37, 0.09, 0.007 \text{ cm}$ while $p_\pi^T \sim 195, 265, 480, 990 \text{ MeV}$ yields 1σ impact parameter resolutions of $\sigma_b \sim 120, 90, 50, 25 \mu\text{m}$. We will explore a signal based on events defined by an appropriate trigger and the presence of one or more large- b charged pions. For the trigger, we will employ a requirement of substantial missing energy. So, we are once again dealing with the HIP signature.

Once $\Delta m_{\tilde{\chi}_1} > 1$ GeV a HIP signature will not be useful and we must consider the chargino decay to be prompt. This is because the largest possible impact parameter is only a few times the 1σ value for the resolution and will be dominated by fakes. This leads us to one of two completely different types of analysis.

(f) $\gamma + \cancel{E}_T$ and jets+ \cancel{E}_T signals:

For some interval of $\Delta m_{\tilde{\chi}_1}$ (e.g. $200 \text{ MeV} \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 300 \text{ MeV}$ at the DELPHI LEP/LEP2 detector — see later — or, perhaps, $1 \text{ GeV} \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 10 - 20 \text{ GeV}$ at the Tevatron) the decay products (hadron(s) or $\ell\nu$) produced along with the $\tilde{\chi}_1^0$ will be too soft to be distinctively visible in the main part of the detector and at the same time high-impact-parameter tracks associated with chargino decay will not be apparent. One will then have to detect chargino production as an excess of events with an isolated photon or missing energy above a large $\gamma + \cancel{E}_T$ or jet(s)+ \cancel{E}_T background. In the jet(s)+ \cancel{E}_T case, the most reliable signal will result from requiring exactly one jet, i.e. monojet+ \cancel{E}_T . For some values of the chargino mass and $\Delta m_{\tilde{\chi}_1}$, an excess in these channels could confirm the SVX signals discussed earlier.

(g) standard mSUGRA signals:

For large enough $\Delta m_{\tilde{\chi}_1}$, the extra lepton or hadron tracks from $\tilde{\chi}_1^\pm$ decay will be sufficiently energetic to be detected and will allow identification of chargino production events when associated with a photon or missing energy trigger. A detailed simulation is required to determine exactly how large $\Delta m_{\tilde{\chi}_1}$ needs to be for this signal to be visible above backgrounds. At LEP/LEP2, backgrounds are sufficiently small that the extra tracks are visible for $\Delta m_{\tilde{\chi}_1} \gtrsim 300 \text{ MeV}$ in association with a photon trigger while standard mSUGRA searches based on missing energy and jets/leptons require $\Delta m_{\tilde{\chi}_1} \gtrsim 3 \text{ GeV}$. At a hadron collider we estimate that $\Delta m_{\tilde{\chi}_1} \gtrsim 10 - 20 \text{ GeV}$ will be necessary to produce leptons or jets sufficiently energetic to produce a distinctive event assuming a missing energy trigger.

In order to assist the reader with our shorthand notations, Table 3 gives shortened definitions for our signals.

The backgrounds to and efficiencies for all these various signals will be different at a hadron collider vs. an e^+e^- collider, and will be detector dependent. Further, at a hadron collider, gluino production can greatly enhance the various signals outlined above. In particular, gluino production leads to a missing energy signal when the gluinos decay invisibly, and to LHIT, TOF, DIT, CT, STUB and/or HIP signals when $\tilde{g} \rightarrow \tilde{\chi}_1^\pm q'\bar{q}$ and the $\tilde{\chi}_1^\pm$ is long-lived.

| Signal | Definition |
|-------------------------|--|
| LHIT | Long, heavily-ionizing (≥ 2 MIP's as measured by SVX+CT+PS), large- p_T track that reaches the MC. The energy deposit in the HC in the track direction must be consistent with expected ionization energy deposit for the β measured (using TOF and/or SVX+CT+PS), i.e. no hadronic energy deposit. |
| TOF | A large- p_T track seen in the SVX and CT along with a signal in the TOF delayed by 500 ps or more (vs. a particle with $\beta = 1$). HC energy deposit (in the direction of the track) is required to be consistent with the ionization expected for the measured β (i.e. no hadronic deposit). |
| DIT | An isolated, large- p_T track in the SVX and CT that fails to reach the MC and deposits energy in the HC no larger than that consistent with ionization energy deposits for the measured (using SVX+CT+PS) β . Heavy ionization in the SVX+CT+PS, corresponding to $\beta < 0.8$ or $\beta < 0.6$ (DIT8 or DIT6), may be required. |
| KINK | A track that terminates in the CT, turning into a soft, but visible, charged-pion daughter-track at a substantial angle to parent. |
| STUB | An isolated, large- p_T (as measured using SVX) track that registers in all SVX layers, but does not pass all the way through the CT. Energy deposits in the EC and HC in the direction of the track should be minimal. |
| SNT | One or more STUB tracks with no additional trigger. Heavy ionization of the STUB in the SVX, corresponding to $\beta < 0.6$ (SNT6), may be required. |
| SMET | One or more STUB tracks with an $\cancel{E}_T > 35$ GeV trigger. Heavy ionization of the STUB in the SVX, corresponding to $\beta < 0.6$ (SMET6), may be required. |
| HIP | A high-impact-parameter ($b \geq 5\sigma_b$) track in the SVX, with large \cancel{E}_T triggering, perhaps in association with a visible KINK in the SVX. |
| $\gamma + \cancel{E}_T$ | Isolated, large- p_T photon and large \cancel{E}_T . |
| monojet+ \cancel{E}_T | Large- p_T jet and large \cancel{E}_T . |
| mSUGRA-like | jet(s)+ \cancel{E}_T , tri-leptons, like-sign di-leptons, <i>etc.</i> , except that the cross section for the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ tri-lepton signal can be suppressed. |

Table 3: Summary of signals. MIP refers to a minimally-ionizing-particle such as a $\beta = 1$ muon. For detector component notation, see Table 2.

2 Collider Phenomenology of degenerate models

Although our main focus will be on Tevatron RunII, it is useful to summarize which of the above signals have been employed at LEP2 and the resulting constraints on the degenerate scenarios we are considering.

2.1 Lepton Colliders

As discussed above and in Refs. [3, 4, 5], collider phenomenology depends crucially on $\Delta m_{\tilde{\chi}_1}$. Most importantly, SUSY detection depends on which aspects (if any) of the $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ final state are visible.

- If the $\tilde{\chi}_1^\pm$ decay products are soft and the $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production is otherwise untagged, the event may be indistinguishable from the large $e^+e^- \rightarrow e^+e^- \gamma\gamma \rightarrow e^+e^- + \text{soft background}$. In this case, one will need to tag $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production. The proposal of Ref. [3] is to employ a photon tag. Such a photon can arise from initial or final state radiation of a photon, denoted as ISR. Even with an ISR tag, it is possible that the $\tilde{\chi}_1^+$ and $\tilde{\chi}_1^-$ will both be effectively invisible because of the softness of their decay products and the lack of a vertex detector signal. In this case, $\gamma \tilde{\chi}_1^+ \tilde{\chi}_1^-$ production is observable as a $\gamma \cancel{M}$ signature, which is distinguishable from the $\gamma \nu \bar{\nu}$ process by the threshold in the missing mass variable $\cancel{M} = \sqrt{(p_{e^-} + p_{e^+} - p_\gamma)^2}$ at $\cancel{M} = 2m_{\tilde{\chi}_1^\pm}$. The exact mass reach in $m_{\tilde{\chi}_1^\pm}$ depends upon available luminosity and machine energy. Estimates were presented in Ref. [3], which we summarize for the $M_2 < M_1 \ll |\mu|$ scenario (1). At LEP2, for $L = 125 \text{ pb}^{-1}$ per experiment, no improvement was found over the $m_{\tilde{\chi}_1^\pm} < 45 \text{ GeV}$ limit coming from LEP1 Z -pole data on $Z \rightarrow \text{invisible}$ decay channels. At the NLC, the prospects are better: with $L = 50 \text{ fb}^{-1}$, the $\gamma \cancel{M}$ channel will be sensitive up to $m_{\tilde{\chi}_1^\pm} \sim 200 \text{ GeV}$. In scenario (2), both $\gamma \tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\gamma \tilde{\chi}_1^0 \tilde{\chi}_2^0$ will have significant rates and a common threshold in \cancel{M} , and the discovery reach is similar to that in scenario (1).
- The experimental situation is greatly improved if the LHIT signal can be employed or if the soft pions from the $\tilde{\chi}_1^\pm$ decays in $\gamma \tilde{\chi}_1^+ \tilde{\chi}_1^-$ events can be detected. This is most clearly illustrated by summarizing the analysis from DELPHI at LEP2 [15]. This analysis employs (in order of increasing radius from the beampipe) their central ID and TPC tracking devices and the ring-imaging Cherenkov device RICH. (For details regarding these devices, please refer to Ref. [15].)
 - For scenario (1) or (2), when $\Delta m_{\tilde{\chi}_1} \lesssim 200 \text{ MeV}$, the charginos are sufficiently long-lived to produce one of two signals for $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production.
 - (a) For $\Delta m_{\tilde{\chi}_1} \lesssim m_\pi$, the charginos produce heavily-ionizing tracks (LHIT's) recognizable by high specific ionization in the TPC or by the absence of Cherenkov light in the RICH.

(b) For $m_\pi \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 200$ MeV, both the charginos and their soft pion daughters yield visible tracks in the central tracking devices (the ID and the TPC, located in the region $10 \text{ cm} < r < 1 \text{ m}$). A clean signal is provided by demanding two primary particle tracks emitted in opposite hemispheres, each decaying to a soft, charged daughter moving at a substantial angle to the primary track. This type of signal is called a KINK.

Note that no additional trigger is required for either signal. As a result, by combining (a) and (b), DELPHI is able to exclude $m_{\tilde{\chi}_1^\pm}$ out to nearly the kinematic limit (currently 90 GeV).

- When $\Delta m_{\tilde{\chi}_1} \gtrsim 3$ GeV, the decay products of the $\tilde{\chi}_1^\pm$ become easily visible, and the standard mSUGRA search results apply; the $\tilde{\chi}_1^\pm$ is excluded out to the kinematic limit (90 GeV for the data sets analyzed), except for the case of a relatively light sneutrino, for which the $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ cross section is smaller and the limit does not extend past 75 GeV.
- For $200 \text{ MeV} \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 3$ GeV, the chargino tracks are not long enough to use the ID/TPC kink signature, and the chargino decay products are too soft to provide a clear signature on their own. In this case, one must overcome the very large $\gamma\gamma$ collision background rate for events containing only soft tracks by tagging the chargino pair production event. As proposed in Ref. [3], DELPHI employs an ISR photon tag. The photon is required to have energy above 4 GeV and the recoil mass \cancel{M} is required to be above 96 GeV (which eliminates all but the virtual Z tail of $\gamma Z^* \rightarrow \gamma\nu\bar{\nu}$ events and the non-resonant contributions). Visible energy (excluding the photon) is required to be less than a few percent of \sqrt{s} (the exact value depends upon the $\Delta m_{\tilde{\chi}_1}$ value being probed). Finally, in order to essentially eliminate the $\gamma\nu\bar{\nu}$ background, the event is required to contain soft charged tracks consistent with the isolated pions expected from the chargino decays. DELPHI observed no events after all cuts. For scenario (1) and a heavy (light) sneutrino, this excludes $m_{\tilde{\chi}_1^\pm} \lesssim 62$ GeV (49 GeV) for $0.3 \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 3$ GeV ($0.5 \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 3$ GeV). The gap from $0.2 - 0.3$ GeV ($0.2 - 0.5$ GeV) arises because of the low efficiency for detecting very soft pions.² Finally, for scenario (2), the ISR signature excludes $m_{\tilde{\chi}_1^\pm} \lesssim 48$ GeV for $0.3 \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 3$ GeV and $m_{\tilde{\chi}_1^\pm} \lesssim 50$ GeV for $1 \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 3$ GeV.

Thus, there is a gap from just above $\Delta m_{\tilde{\chi}_1} \sim 200$ MeV to at least 300 MeV for which the chargino is effectively invisible. DELPHI finds that the $\gamma\cancel{M}$ signature, discussed earlier, is indeed insufficient to improve over the $m_{\tilde{\chi}_1^\pm} \gtrsim 45$ GeV limit from Z decays. We are uncertain whether DELPHI explored the use of high-impact-parameter tracks in their vertex detector (in association with the ISR trigger) to improve their sensitivity (by sharply reducing the $\gamma\nu\bar{\nu}$ background) in these gap regions.

²With the ISR tag, the $\gamma\gamma$ background is completely negligible.

2.2 Hadron Colliders

At hadron colliders, typical signatures of mSUGRA are tri-lepton events from neutralino-chargino production, like-sign di-leptons from gluino pair production, and multijets+ \cancel{E}_T from squark and gluino production. The tri-lepton signal from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production and the like-sign di-lepton signal from $\tilde{g}\tilde{g}$ production are both suppressed when $\Delta m_{\tilde{\chi}_1}$ is small by the softness of the leptons coming from the $\tilde{\chi}_1^\pm$ decay(s). In $M_2 < M_1 \ll |\mu|$ scenarios, the tri-lepton signal is further diminished by the suppression of the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ cross section. In $|\mu| \ll M_2, M_1$ scenarios, $m_{\tilde{\chi}_2^0} \simeq m_{\tilde{\chi}_1^0}$ and even though the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ cross section is not suppressed the $\tilde{\chi}_2^0$ decay products, like those of the $\tilde{\chi}_1^\pm$, are very soft, yielding further suppression of the tri-lepton signal. Provided that $m_{\tilde{g}}$ is light enough, the most obvious signal for SUSY in degenerate models is jet(s) plus missing energy. Even if the gluino is rather degenerate with the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$, it has been shown [4] (see also [1]) that the Tevatron and LHC will probe a significant (albeit reduced compared to mSUGRA boundary conditions) range of $m_{\tilde{g}}$. This is true since initial state gluon radiation can be used to ‘tag’ the missing energy. This search can also be augmented by the $\gamma\tilde{g}\tilde{g}$ process, where the γ is the tag. As $m_{\tilde{g}} - m_{\tilde{\chi}_1^\pm}$ increases, the jets from $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^\pm + q\bar{q}\tilde{\chi}_1^0$ decays become visible and the jet(s)+ \cancel{E}_T signature initially becomes stronger [4] despite the decrease in the $\tilde{g}\tilde{g}$ production cross section. However, it is entirely possible that the gluino is much heavier than the light $\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ states and that the $\tilde{g}\tilde{g}$ production rate (at the Tevatron at least) will be quite suppressed. In this case, the ability to detect events in which the only directly produced SUSY particles are light neutralino and chargino states could prove critical. In the remainder of this paper, we consider the sfermion, and heavier chargino and neutralino states to be extremely heavy, and investigate methods to probe degenerate models at the Tevatron. Expectations for scenarios where the gluino has a mass comparable to $\tilde{\chi}_1^\pm$ will be given less discussion. First, we study whether photon tagging (which we noted above is useful at a lepton collider) or jet tagging (as employed in many studies) might provide a viable signal when the $\tilde{\chi}_1^\pm$ decay is effectively prompt and its decay products are too soft to be visible in the detector. Later, we consider the modifications to this picture when the $\tilde{\chi}_1^\pm$ decay is not prompt.

In the following, we perform particle level studies using either the processes contained in the PYTHIA 6.125 [16] event generator or by adding external processes (several of the $\gamma+X$ processes considered here) into PYTHIA. A calorimeter is defined out to $\eta = 4.4$ with a Gaussian E_T resolution of $\sigma_{E_T} = 80\%/\sqrt{E_T}$. Jets with $E_T > 5$ GeV and $R = 0.5$ are reconstructed to define \cancel{E}_T . Non-Gaussian contributions will be estimated as described later. Charged track momenta and impact parameters b are unsmeared, but the effects of detector resolution on b are included.

2.2.1 Pure γ or jet and \cancel{E}_T signatures

One of the most challenging possibilities in degenerate models is when the $\tilde{\chi}_1^\pm$ decay is prompt and its decay products are too soft to be visible. At leading order in perturbation theory, $\tilde{\chi}_1^\pm(\rightarrow \tilde{\chi}_1^0 + \text{soft})\tilde{\chi}_1^0$ and $\tilde{\chi}_1^+(\rightarrow \tilde{\chi}_1^0 + \text{soft})\tilde{\chi}_1^-(\rightarrow \tilde{\chi}_1^0 + \text{soft})$ production provide no good signature since the missing transverse momenta of the LSP's essentially cancels and the soft decay products are obscured by detector resolution and the combined effect of the underlying event and fragmentation/hadronization. However, it may still be possible to observe the transverse momentum of the LSP's if a high- p_T jet or photon is also produced in an event.

In the absence of mismeasurements, the major physics background to $\gamma + \cancel{E}_T$ at the Tevatron is $\gamma Z(\rightarrow \nu\bar{\nu})$ and $\gamma\tau^\pm\nu_\tau$ production, where $\tau(\rightarrow \cancel{E}_T + \text{soft})$. In reality, mismeasurements of jets can produce a false \cancel{E}_T , and the loss of a track can cause an electron to fake a photon. A realistic search strategy should account for these potential backgrounds and/or rely on cuts that reduce them to a manageable level. If we ignore such backgrounds, we need to understand under what conditions this is reasonable. We can gain some insight into the relative importance of mismeasurement backgrounds from RunI analyses. The DØ RunI measurement of the $\gamma Z(\rightarrow \nu\bar{\nu})$ signal (which is a *background* to our signature) has a background from $W(\rightarrow e^\pm\nu_e)$ when the e fakes a γ . For RunI, the fake probability was roughly a constant with magnitude $R_{e\rightarrow\gamma} = 5 \times 10^{-3}$. The background estimate in the DØ analysis is well reproduced by generating $W(\rightarrow e^\pm\nu_e)$ events with PYTHIA, replacing the e with a γ , weighting the event by an additional factor $R_{e\rightarrow\gamma}$, and performing all other cuts. The value of S/B is about 0.3, but the W contribution becomes negligible once $p_T^\gamma \gtrsim 50 - 60$ GeV, which is beyond the Jacobian peak for the electron p_T spectrum. Another significant background arises from $\gamma + \text{jet}$, where the jet fakes \cancel{E}_T . For $\cancel{E}_T > 40$ GeV, this probability can be conservatively estimated³ at $R_{j\rightarrow\cancel{E}_T} = 10^{-4}$. This background can also be reproduced by generating $\gamma + q, \gamma + g$ events with PYTHIA, demanding only one reconstructed jet with $E_T > 15$ GeV, discarding this jet, weighting the event by an additional factor $R_{j\rightarrow\cancel{E}_T}$, calculating \cancel{E}_T from the sum of all remaining jets, and performing all remaining cuts. Once $\cancel{E}_T > 50$ GeV, this background is roughly 5% of the $\gamma Z(\rightarrow \nu\bar{\nu})$ signal, and decreases quickly with increasing \cancel{E}_T . Since we can reproduce the mismeasurement backgrounds in a simple manner, we feel confident that we can reasonably estimate the full background. Additionally, we will set our cuts so that the mismeasurement backgrounds are smaller than the physics ones, which, for the chargino signal, will be dominated by $\gamma Z(\rightarrow \nu\bar{\nu})$. To reflect the detector improvements in Run II, we use the factor $R_{e\rightarrow\gamma} = 10^{-3}$.

We have studied $\gamma\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\gamma\tilde{\chi}_1^+\tilde{\chi}_1^0$ production (computed for various values of M_2 taking $M_1 =$

³Note that $R_{j\rightarrow\cancel{E}_T}$ represents a non-Gaussian component to the \cancel{E}_T resolution; the Gaussian component is already included in our calorimeter simulation.

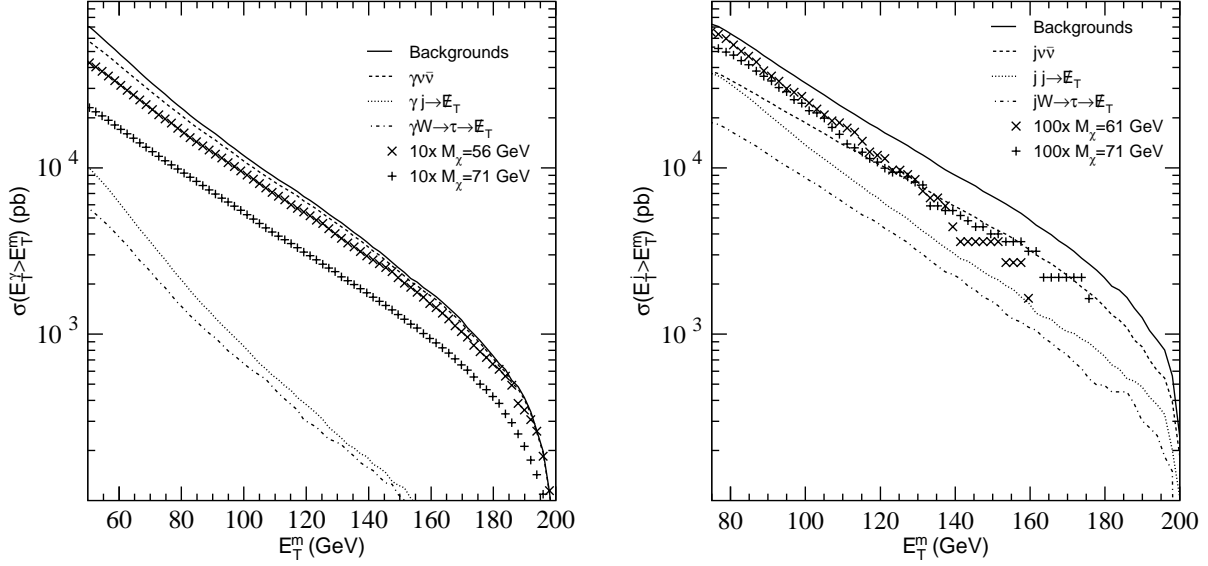


Figure 2: Comparison of the signal and backgrounds for $\gamma + \cancel{E}_T$ and $j + \cancel{E}_T$ searches at the Tevatron for $\sqrt{s} = 2$ TeV. In (a), we plot the sum of the $\gamma\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\gamma\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ cross sections integrated over $E_T^\gamma, \cancel{E}_T > E_T^{\min}$; the additional cuts imposed are given in of Eq. (4). Results are given for $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0} \sim 56$ GeV and ~ 71 GeV; the signal has been multiplied by a factor of 10. In (b), we plot the $j\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $j\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ ‘monojet’ cross sections integrated over $E_T^j, \cancel{E}_T > E_T^{\min}$, after imposing the additional cuts given in Eq. (5). Results are presented for $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0} \sim 61$ GeV and ~ 71 GeV; the signal has been multiplied by a factor of 100.

$1.5M_2$, $\tan\beta = 5$ and $\mu = 1$ TeV — typically, $m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0}$ is close to M_2) and the expected backgrounds identified above. Because only \cancel{E}_T (and not \cancel{E}) can be measured, we cannot perform a cut that eliminates the real Z background from γZ production. At best, the distributions for signal and background in E_T^γ may be sufficiently different that a cut requiring high E_T^γ will allow a reasonable signal-to-background ratio while retaining adequate cross section for the signal. To demonstrate this, we plot in Fig. 2(a) the $\gamma\tilde{\chi}_1^+\tilde{\chi}_1^-$ and $\gamma\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ integrated signal and $\gamma + \cancel{E}_T$ background (and some components thereof) as a function of a minimum accepted value for E_T^γ . (Note that the signal is multiplied by a factor of 10 in the figure.) Our nominal cuts are:

$$\begin{aligned}
 E_T^\gamma &> E_T^{\min}, \quad \cancel{E}_T > E_T^{\min}, \quad |\eta^\gamma| < 2.0, \\
 &\text{no jets with } E_T > 15 \text{ GeV}, \quad |\eta| < 3.5, \\
 &\text{no } e's \text{ or } \mu's \text{ with } p_T > 5 \text{ GeV}, \quad |\eta| < 2.0.
 \end{aligned} \tag{4}$$

While the signal is somewhat flatter, $S/B > 0.1$ is only achieved if a very high E_T^{\min} cut is imposed.

However, the signal cross sections are rapidly decreasing as the cut is increased, so we cannot take too high a E_T^{\min} cut. To quantify the difficulty, consider $m_{\tilde{\chi}_1^\pm} \sim 60$ GeV. For $E_T^{\min} = 50$ GeV (100 GeV), one finds $\sigma(\gamma\tilde{\chi}_1^+\tilde{\chi}_1^- + \gamma\tilde{\chi}_1^\pm\tilde{\chi}_1^0) \sim 10$ fb (1.5 fb) compared to $\sigma_B(\gamma\cancel{E}_T) \sim 211$ fb (27 fb), so that these cuts yield $S/B \sim 0.05$ (0.06) and $S/\sqrt{B} = 3.8$ (1.6). Thus, we will be able to see a signal in the $\gamma + \cancel{E}_T$ channel for $m_{\tilde{\chi}_1^\pm} \sim 60$ GeV only if systematics are understood at the $S/B \sim 0.05$ level. If $S/B \gtrsim 0.1$ is required, the $\gamma + \cancel{E}_T$ signal can probe only $m_{\tilde{\chi}_1^\pm} \lesssim 50$ GeV. Either value is only a marginal improvement over the 45 GeV lower bound deriving from LEP Z -pole data when the chargino decay products cannot be detected (i.e. when $200 \text{ MeV} \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 300 - 500 \text{ MeV}$). Even more importantly, both values are below the limits set by DELPHI once $\Delta m_{\tilde{\chi}_1} \geq 300 - 500 \text{ MeV}$. In scenario (2), the signal cross section sum will be somewhat smaller than in scenario (1), and S/B will typically be too small to extract a signal from the data.

Given the importance of achieving a very small systematic error level in order to extend the LEP/LEP2 limits on an invisible chargino, it is worth noting that systematic errors *do* decrease with integrated luminosity, and many RunI analyses have systematic errors that are smaller than or the same size as the statistical error. The RunII situation should be much better than in RunI. Furthermore, we have not exploited any difference in shape between the signal and background, which may increase the significance of the signal. If any other distinguishing characteristics of the signal can be observed, or if there are other sources of chargino production, then the upper limit of $m_{\tilde{\chi}_1^\pm}$ for which the $\gamma + \cancel{E}_T$ signature is viable could be significantly larger than estimated here.

Given the somewhat pessimistic results for the $\gamma + \cancel{E}_T$ signal, it is worth exploring the standard SUSY jets+ \cancel{E}_T signal, which will have a larger event rate for comparable cuts. As compared to the normal mSUGRA scenario, the softness of the $\tilde{\chi}_1^\pm$ decay products implies that the jets+ $\tilde{\chi}_1^+\tilde{\chi}_1^-$ events will have much lower jet multiplicity. After including the effects of initial state gluon radiation, many events have a monojet nature. The published RunI analyses have taken advantage of the jet multiplicity to control the QCD backgrounds, and are of little help in understanding potentially large monojet backgrounds. Thus, we will consider applying the standard mSUGRA 3-jet+ \cancel{E}_T cuts to a Monte Carlo prediction of the signal, using the published background estimates to set limits. Since the parton showering machinery can generate several jets per event, some signal events will pass the cuts. However, as discussed below, we find that there are substantial uncertainties in the Monte Carlo predictions for the multijet signal rate when the multiple jets are generated from parton showering and not by sparticle decays. Thus, we also consider a monojet signature for which we believe that the monojet+ \cancel{E}_T Monte Carlo signal rate computed using parton showering will be more reliable. This necessitates a study of the mismeasurement background. As discussed below, we believe that this and other monojet+ \cancel{E}_T backgrounds can be understood and convincingly controlled.

We consider the monojet+ \cancel{E}_T signal first. To illustrate the size of the signal from jet+ $\tilde{\chi}_1^+\tilde{\chi}_1^-$ and

jet+ $\tilde{\chi}_1^+ \tilde{\chi}_1^0$ compared to background, we proceed much as in the case of the γ tag. Our specific cuts are:

$$\begin{aligned} E_T^j &> E_T^{\min}, \quad \cancel{E}_T > E_T^{\min}, \quad |\eta^j| < 3.5, \\ \text{no other jets with } E_T &> 15 \text{ GeV}, \quad |\eta| < 3.5, \\ \text{no } e's \text{ or } \mu's \text{ with } p_T &> 5 \text{ GeV}, \quad |\eta| < 2.0. \end{aligned} \tag{5}$$

We claim that these cuts are such that the physics backgrounds from $j\nu\bar{\nu} \rightarrow j\cancel{E}_T$ and $jW(\rightarrow \tau \rightarrow \cancel{E}_T)$ are larger than the mismeasurement background. The major mismeasurement background to a monojet+ \cancel{E}_T search is jet+jet production, where one jet fakes \cancel{E}_T . We will only consider values of E_T^{\min} above 75 GeV, which means that \cancel{E}_T will always be required to be above the threshold employed for the RunI multijet analyses. To estimate the mismeasurement background, we have generated all QCD two parton processes with PYTHIA, and retained only those events containing only one or two jets with $E_T > 15$ GeV. If there are two jets, we then randomly discard one of the two and weight the event by a factor $2 \times R_{j \rightarrow \cancel{E}_T}$. We then impose the cuts of Eq. (5). For $E_T^j > E_T^{\min} = 75$ GeV, we arrive at a cross section estimate of 4 pb. The dominant physics backgrounds, $Z(\rightarrow \nu\bar{\nu})$ +jet and $W(\rightarrow \tau\nu_\tau)$ +jet, contribute 4 and 1.6 pb for the same cuts (note, we are far beyond the Jacobian peak, so that $W(\rightarrow \ell\nu_\ell)$ +no jet, where $\ell = e, \mu, \tau$, can be ignored). Thus, even if our estimate of the QCD background is off by a factor of 2, this will not substantially bias an exclusion limit obtained using Gaussian statistics. After including $t\bar{t}$, single top, gauge boson pairs, and $W(\rightarrow e\nu_e, \mu\nu_\mu)$ +jet backgrounds, the full background for the cuts of Eq. (5) and $E_T^{\min} = 75$ GeV is about 10 pb.

Figure 2(b) shows the integrated cross section for the background and signal (signals are multiplied by 100 in the figure) as a function of E_T^{\min} . It is clear that the background is so severe that the monojet+ \cancel{E}_T channel will be much less useful than the $\gamma + \cancel{E}_T$ channel. The relative behavior of the two channels is easy to understand. At $E_T^{\min} = 75$ GeV, we observe that the Z backgrounds differ by a factor of about 63. Naively, we estimate that they should differ by $2\alpha_s/(\alpha Q_u^2) \simeq 58$, where $\alpha = 1/128$ and the factor of 2 accounts for the 2 different topologies, $qg \rightarrow Zq$ and $q\bar{q} \rightarrow Zg$. On the other hand, the signal is not so suppressed in switching from the $j + \cancel{E}_T$ to $\gamma + \cancel{E}_T$ channel, since final state, photon radiation off the charginos is important. Also, since we generated the $j + \cancel{E}_T$ signal using parton showering, we underestimate the signal cross section at high \cancel{E}_T . Finally, we note that the mismeasurement backgrounds are much more relevant for the $j + \cancel{E}_T$ channel. To see if there is any hope for this discovery channel, we have varied the E_T^{\min} cut in search of a value such that $S/B > 0.1$ and such that there are at least 5 events for $L = 30 \text{ fb}^{-1}$. We never satisfy these constraints for $m_{\tilde{\chi}_1^\pm} > 45$ GeV, so no limit beyond that from LEP Z -pole data can be set using this channel. Nonetheless, as explained below, a significant signal may appear in the $j + \cancel{E}_T$ channel if there are other sources of chargino production.

We will now turn momentarily to the multijet+ \cancel{E}_T signal. At the same time, we will also consider

the more optimistic possibility that the gluino mass is small enough that $\tilde{g}\tilde{g}$ pair production has a reasonable rate at the Tevatron. In particular, we consider the limit, previously analyzed in Ref. [4] and motivated in the O-II model, that the gluino is almost degenerate in mass with $\tilde{\chi}_1^\pm$. The results of Ref. [4] were that $m_{\tilde{g}} = 150$ GeV could be excluded with $L = 2 \text{ fb}^{-1}$ of data, and that this reach could not be extended using higher L if one demanded $S/B > 0.2$. The exclusion was based on background estimates from DØ and CDF for their RunI 3 jet+ \cancel{E}_T searches. We have repeated the analysis of Ref. [4] using PYTHIA instead of ISAJET [17]. We find that we cannot reproduce all of the Ref. [4] results, and the reasons (to be discussed below) suggest that one may not wish to trust results obtained via Monte Carlo for a multijet+ \cancel{E}_T signal of the type considered here, in which the jets are generated entirely by parton showering. For example, consider $m_{\tilde{g}} = 75$ GeV. Using PYTHIA, we find roughly half the signal cross section (compared to [4]) after the DØ cuts. This discrepancy arises because of the details of parton showering used in ISAJET (Ref. [4]) as compared to PYTHIA (our study). For the first, soft-gluon emission in a shower, PYTHIA restricts the polar angle of the branching to be smaller than the angle of the color flow, while ISAJET does not. As a result, the soft gluons in ISAJET are more widely distributed, and the resultant jet multiplicity is higher. Indeed, when we turn off the angular ordering effect in PYTHIA, we reproduce the ISAJET results. For larger $m_{\tilde{g}}$, however, the discrepancy remains, and is not entirely resolved. If we use the PYTHIA results, the Ref. [4] Tevatron limit on $m_{\tilde{g}}$ is reduced to $m_{\tilde{g}} \sim 95 - 100$ GeV. However, the comparison of the two Monte Carlo programs suggests that one cannot trust a parton showering result in degenerate scenarios for 3 hard, well-separated jets.

Thus, we return to our proposed monojet signature to estimate the potential of the Tevatron for probing the $m_{\tilde{g}} \sim m_{\tilde{\chi}_1^\pm} \simeq m_{\tilde{\chi}_1^0}$ scenario. As already noted, the \cancel{E}_T signature is enhanced by $q\bar{q}, gg \rightarrow \tilde{g}\tilde{g}$, where $\tilde{g} \rightarrow q'\bar{q}\tilde{\chi}_1^\pm, q\bar{q}\tilde{\chi}_1^0$. For small $m_{\tilde{g}} - m_{\tilde{\chi}_1^\pm}$ the q, q', \bar{q} are typically too soft to be counted as jets and, of course, in the study of this section we are assuming that the $\tilde{\chi}_1^\pm$ decay products are not visible. The monojet still comes from parton showering. In Fig. 3(a) we plot the luminosity required for $S/\sqrt{B} = 1.96$ or 5 and $S/B > 0.1$ or 0.2 as a function of $m_{\tilde{g}}$. We have employed the cuts of Eq. (5), searching for the $E_T^{\min} > 75$ GeV that maximizes S/\sqrt{B} while satisfying the given S/B criteria. (For lower $m_{\tilde{g}}$, $E_T^{\min} = 75$ GeV is always best; for the highest $m_{\tilde{g}}$ values the best E_T^{\min} increases.) With the enhanced production cross sections, we observe that it is much easier to achieve $S/B > 0.2$ and a gluino with $m_{\tilde{g}} = 150$ GeV should be discovered or excluded early in RunII. However, discovering or excluding $m_{\tilde{g}} = 175$ GeV will require reducing systematics to the extent that an $S/B = 0.1$ signal can be trusted. Specifically, for $S/B > 0.1$, $m_{\tilde{g}} = 175$ GeV can be excluded at 95% CL with $L = 0.3 \text{ fb}^{-1}$ or discovered at the 5σ level with $L = 2 \text{ fb}^{-1}$.

The process $\gamma\tilde{g}\tilde{g}$, where $\tilde{g} \rightarrow \text{soft}$, yielding a $\gamma + \cancel{E}_T$ signal, is complimentary to the monojet+ \cancel{E}_T signal. We follow the same procedure as discussed for the monojet+ \cancel{E}_T signal, except that we employ the cuts of Eq. (4) and require $E_T^{\min} > 50$ GeV. The luminosity required to discover or exclude a given

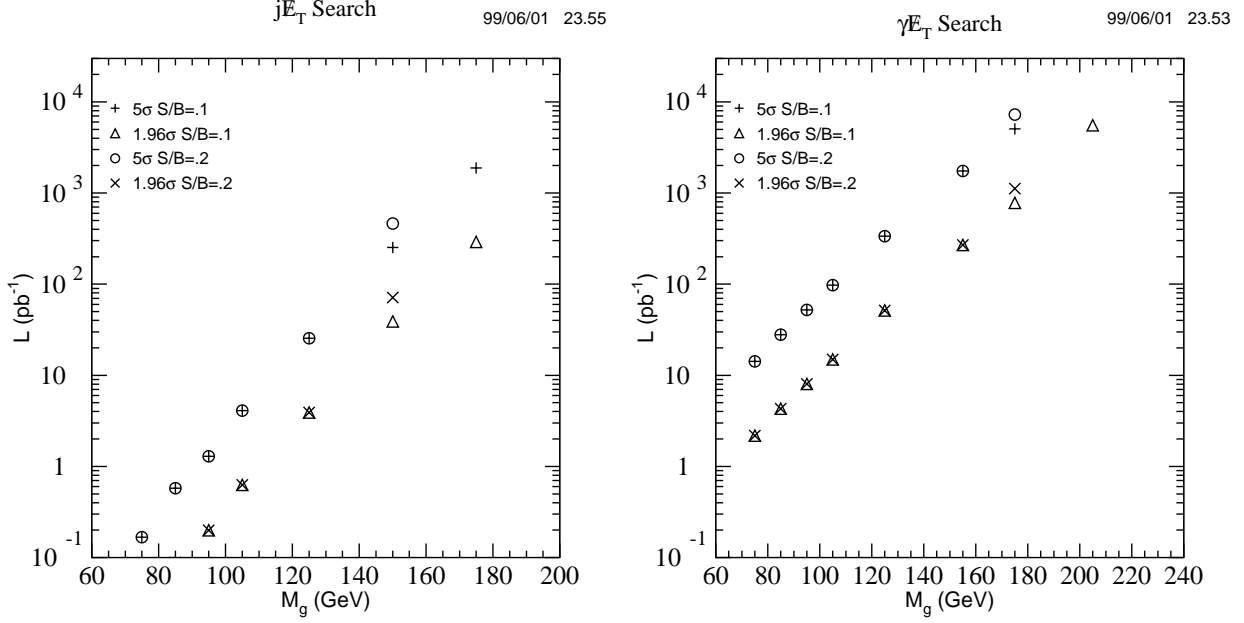


Figure 3: Integrated luminosity (in pb) required to observe ($S/\sqrt{B} = 5$) or exclude at 95% CL ($S/\sqrt{B} = 1.96$) a monojet+ \cancel{E}_T or $\gamma + \cancel{E}_T$ signal from $\tilde{g}\tilde{g}$ production, when $m_{\tilde{g}} \simeq m_{\tilde{\chi}_1^+}$. Predictions are shown for signal to background ratios of 0.1 and 0.2. For $m_{\tilde{g}}$ values above those for which points are plotted, S/B is below the required value. For the monojet+ \cancel{E}_T [$\gamma + \cancel{E}_T$] signal we impose the cuts of Eq. (5) [Eq. (4)], optimizing S/\sqrt{B} by scanning over $E_T^{\min} > 75$ GeV [> 50 GeV].

$m_{\tilde{g}}$ using this signal is plotted in Fig. 3(b). Even though the $\gamma + \cancel{E}_T$ signal requires more integrated luminosity to establish a signal for low $m_{\tilde{g}}$, S/B is larger, allowing exclusion out to a larger value of the common chargino/gluino mass; $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{g}} \leq 175$ GeV can be excluded at 95% CL with $L = 1 \text{ fb}^{-1}$ of integrated luminosity even if $S/B > 0.2$ is required.

For purposes of comparison, we note that in an mSUGRA scenario the tri-lepton signature from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production allows one to probe chargino masses up to about 160 GeV for $L = 30 \text{ fb}^{-1}$ when the scalar soft-SUSY-breaking mass is large [18].

We note that the monojet+ \cancel{E}_T and $\gamma + \cancel{E}_T$ signatures should persist (and perhaps even improve somewhat) for $m_{\tilde{g}} - m_{\tilde{\chi}_1^\pm} \sim \text{few} - 10$ GeV and/or $\Delta m_{\tilde{\chi}_1} \sim \text{few} - 10$ GeV.

Before concluding this subsection, we should comment that there are potential contributions from $\tilde{g}\tilde{\chi}_1^\pm$ and $\tilde{g}\tilde{\chi}_1^0$ production that have not been included here. These will depend on the exact values of the squark masses, which are assumed to be heavy. For the remainder of the paper, we assume that the gluino is also very heavy.

2.2.2 LHIT and TOF signatures

In the previous section, we considered the case where the mass splitting was large enough for the chargino decay to be very prompt, but yet too small for the chargino decay products to be visible. In this section, we consider the opposite extreme, namely $\Delta m_{\tilde{\chi}_1}$ sufficiently small that the chargino is so long-lived that it passes through the TOF and enters the muon chambers. For instance, if $\Delta m_{\tilde{\chi}_1} < m_\pi$, then the average $c\tau$ is of order a meter or more. Of course, as noted earlier, the radiatively generated mass splitting makes $\Delta m_{\tilde{\chi}_1} < m_\pi$ somewhat unlikely in the context of the existing models. But, even for $\Delta m_{\tilde{\chi}_1} > m_\pi$ there is a tail of events with large enough $\beta\gamma c\tau$ values for the chargino to reach the muon chambers. Thus, from the experimental point of view it is important to consider signals based on a muon-chamber or TOF signal as a function of $\Delta m_{\tilde{\chi}_1}$.

To distinguish a chargino that reaches the muon chambers from an actual muon without using the TOF, we employ the procedures used by CDF in RunI for identifying a penetrating particle that is sufficiently heavily-ionizing that it cannot be a muon. However, because the DØ inner muon chambers are closer to the interaction point and cover more range in $|\eta|$, it is advantageous to employ the DØ muon chamber configuration (see earlier description). In analogy to the CDF RunI procedure, we first demand a trigger for the event using one track (Track I) that penetrates to the muon chambers. We then examine the triggered events for a track (Track II) that is heavily-ionizing and penetrates to the muon chambers. The specific cuts/requirements we impose in our study are:⁴

Track I and II: $(|\eta| < 1, \beta_\perp \gamma c\tau > 2.7 \text{ m})$ or $(1 < |\eta| < 2, |\beta_z| \gamma c\tau > 4 \text{ m}), \beta > \beta_{\min}$

Track I: $p_T > 15 \text{ GeV}$

Track II: $|\vec{p}| > 35 \text{ GeV}, \beta\gamma < 0.85,$ (6)

where β_{\min} is the minimum velocity ($\simeq 0.4-0.5$) required for the $\tilde{\chi}_1^\pm$ to penetrate to the muon chambers. In Eq. (6), β_\perp is the velocity perpendicular to the side of the box formed by the inner muon chambers (see earlier description) that the chargino eventually passes through, and $\beta\gamma < 0.85$ is the 2MIP requirement. Tracks I and II may be the same track. An event satisfying these cuts will be called an LHIT event and is expected to be background-free.

For small $m_{\tilde{\chi}_1^\pm}$, the $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production cross sections are large before cuts, but the β_{\min} and $\beta\gamma$ requirements accept only a small portion of the full rate. For larger $m_{\tilde{\chi}_1^\pm}$, the cross section decreases, but $\beta\gamma$ is typically smaller. These trends are illustrated in Fig. 4. This figure shows the full

⁴Note that since the CDF procedure was originally designed for looking for massive quarks, they did not impose a requirement of small hadronic energy deposit in the track direction(s). We have not imposed this requirement either. However, for the chargino signal of interest here it could be imposed with little loss of signal event rate were this useful for reducing backgrounds.

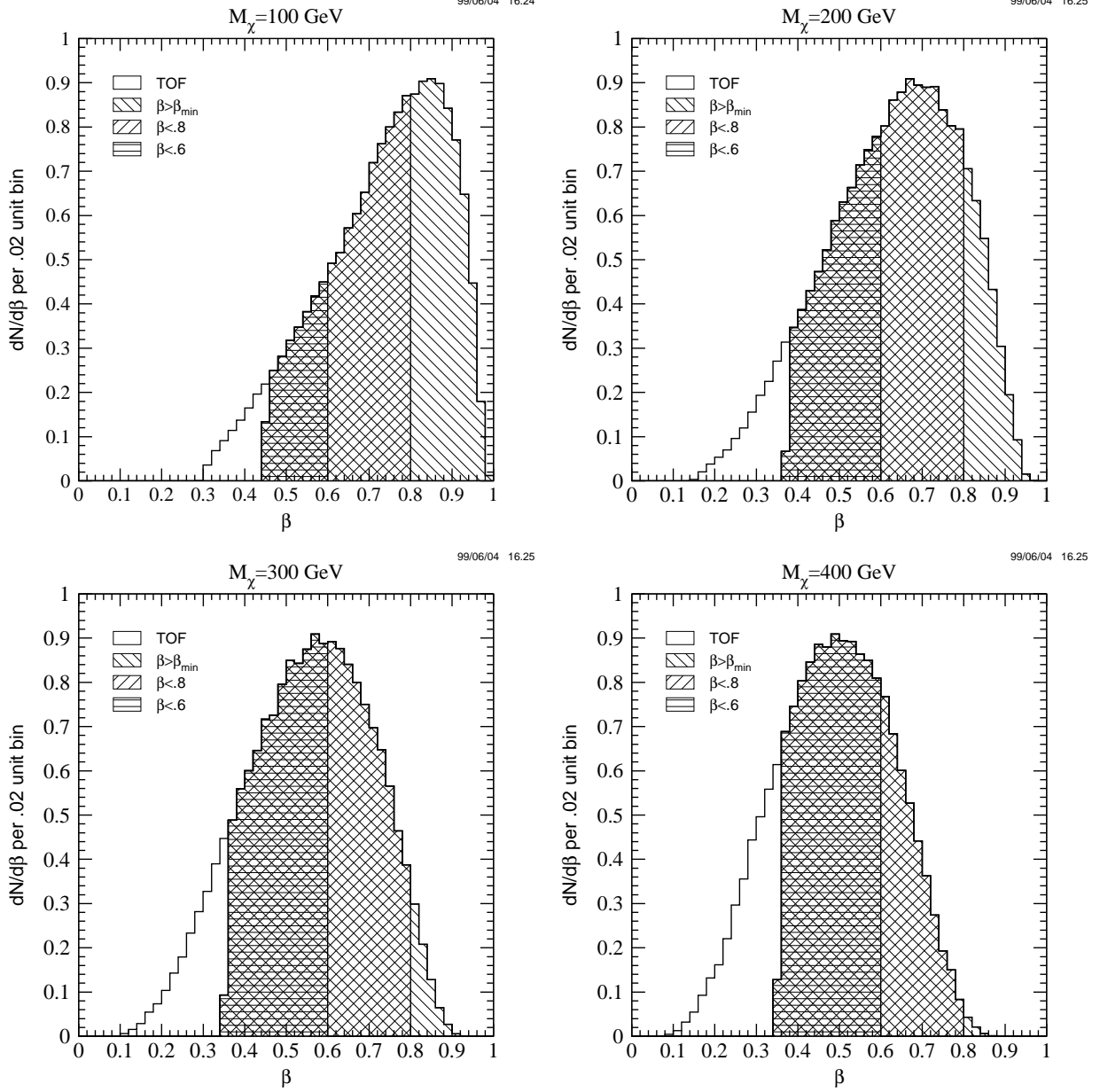


Figure 4: Unnormalized β distributions for events accepted by the non- β cuts of Eq. (6) after requiring that the TOF time delay be > 500 ps. The segments left after imposing various more restrictive β cuts are also shown. Distributions are given for $m_{\tilde{\chi}_1^\pm} = 100, 200, 300$ and 400 GeV.

β distributions for $m_{\tilde{\chi}_1^\pm} = 100, 200, 300$ and 400 GeV that remain after requiring that the chargino pass through the TOF device at least 500 ps later than a particle with $\beta = 1$ (as required in the TOF signal discussed below). The impact of the β_{\min} cut and of various requirements on the maximum value of β is also shown. We see that for $m_{\tilde{\chi}_1^\pm} = 100$ GeV a relatively small slice of the β distribution is retained

after requiring both $\beta > \beta_{\min}$ and $\beta < 0.6$ ($\beta\gamma < 0.75$) or $\beta < 0.65$ ($\beta\gamma < 0.85$). The slice accepted by such cuts is much larger for $m_{\tilde{\chi}_1^\pm} = 400$ GeV.

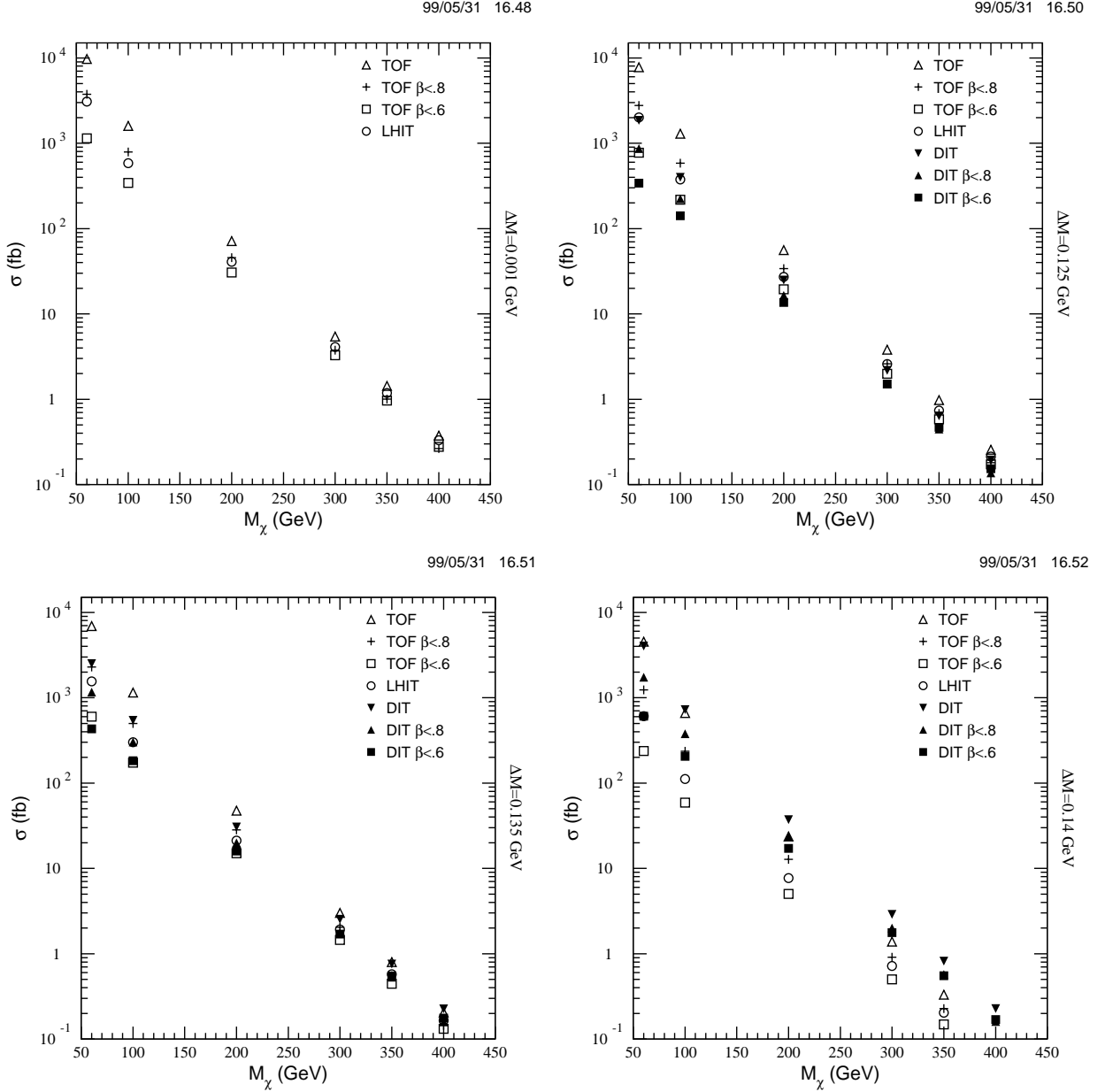


Figure 5: Cross sections for LHIT, TOF and DIT “background-free” signatures at RunII: $\Delta m_{\tilde{\chi}_1} = 0, 125, 135, 140$ MeV.

The cross section obtained after imposing all the cuts of Eq. (6) is plotted as the open circles in Fig. 5 for a selection of $\Delta m_{\tilde{\chi}_1}$ values. For $c\tau = \infty$, $m_{\tilde{\chi}_1^\pm} = 350$ GeV (450 GeV) can be excluded at the 95% CL (3 events predicted, none observed) with 2 (30) fb^{-1} of data. A 5 event discovery would

require $m_{\tilde{\chi}_1^\pm} \leq 325$ GeV (≤ 430 GeV) for $L = 2$ fb $^{-1}$ (30 fb $^{-1}$). The 3 event limits for various $\Delta m_{\tilde{\chi}_1}$ values are summarized in Fig. 12. As expected, the LHIT signal mass reach declines as $\Delta m_{\tilde{\chi}_1}$ increases, and the LHIT signal has vanished by $\Delta m_{\tilde{\chi}_1} = 142.5$ MeV.

Let us now turn to the time-of-flight (TOF) signal for identifying a slow-moving, long-lived chargino. Our procedure for triggering will be exactly as for Track I in the LHIT procedure. We then look for a Track II that satisfies the same cuts as in the LHIT case except that the $\beta\gamma < 0.85$ requirement is replaced by the requirement that Track II arrive at the TOF device at least 500 ps later than would a relativistic track. For the expected 100 ps time resolution of the TOF signal, this corresponds to a 5σ delay in arrival compared to a particle with $\beta \sim 1$. Thus, we replace the $\beta\gamma < 0.85$ requirement by

$$d_{\text{TOF}}/(\beta c) - d_{\text{TOF}}/c > 500 \text{ ps}, \quad (7)$$

where d_{TOF} is the distance to the muon chamber along the direction of flight.

As mentioned previously, for smaller $m_{\tilde{\chi}_1^\pm}$ values the TOF signal accepts a significantly larger range of $\beta\gamma$ than does the heavy-ionization $\beta\gamma < 0.85$ requirement of the LHIT signal. This is clearly apparent from the $m_{\tilde{\chi}_1^\pm} = 100$ and 200 GeV windows of Fig. 4 by comparing the total $\beta > \beta_{\min}$ region to the $\beta_{\min} < \beta < 0.65$ region. However, for large $m_{\tilde{\chi}_1^\pm}$ near the upper limit that can be probed by the LHIT signal (see the $m_{\tilde{\chi}_1^\pm} = 400$ GeV window of Fig. 4) the $\beta < 0.65$ ($\beta\gamma < 0.85$) LHIT cut is not that much less efficient than the TOF cut. Thus, we can anticipate that the TOF signal will be viable for lower luminosity than the LHIT signal if $m_{\tilde{\chi}_1^\pm}$ is not large, but that the TOF signal will not be viable for $m_{\tilde{\chi}_1^\pm}$ values much beyond those reachable by the LHIT signal.

The TOF cross sections as a function of $m_{\tilde{\chi}_1^\pm}$ are given in Fig. 5 for the same $\Delta m_{\tilde{\chi}_1}$ values for which the LHIT cross sections were plotted. As expected, Fig. 5 shows that the TOF signal is much more efficient than the LHIT signal at lower masses, but the upper mass limit attained using the TOF and LHIT signals is the same, e.g. $m_{\tilde{\chi}_1^\pm} \sim 430$ GeV for $L = 30$ fb $^{-1}$ and $\Delta m_{\tilde{\chi}_1} = 125$ MeV.

As already noted, the fact that the TOF and LHIT upper mass limits are the same is due to the fact that the largest $m_{\tilde{\chi}_1^\pm}$ masses that can be probed are such that the $\beta\gamma < 0.85$ requirement is not very restrictive. That such large masses can be probed is due to the s -wave nature of the $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production subprocesses, which, in turn, implies large cross sections in $p\bar{p}$ collisions out to high $m_{\tilde{\chi}_1^\pm}$. This can be contrasted with the result for long-lived staus. The p -wave nature of the $\tilde{\tau}^+ \tilde{\tau}^-$ production subprocesses implies much smaller $p\bar{p}$ cross sections, for which the LHIT signal mass reach is limited to $m_{\tilde{\tau}} \lesssim 145$ GeV. For such masses, the LHIT requirement of $\beta\gamma < 0.85$ is very restrictive. Due to its acceptance of $\beta\gamma$ values substantially beyond 0.85, the TOF signal improves the mass reach to 175 GeV [14].

We have not performed a study as to where additional TOF devices should be placed in order to further optimize the TOF signal. However, we believe that if $c\tau \lesssim 1$ m there would be significant gain

if there were a TOF device in between the EC and the HC (in addition to the TOF device next to the inner muon chambers). With an appropriate electronics design, events with a chargino that reached the inner TOF device but not the muon chamber could be triggered by the inner TOF signal and the presence of a stiff chargino track in the tracker. The time delay of the TOF signal would indicate the mass of the particle, and such events would be background free. However, the mass reach would only improve over the DIT signal discussed below if a heavy-ionization requirement has to be imposed in order that the latter be background free.

2.2.3 DIT signatures

As $\Delta m_{\tilde{\chi}_1}$ increases above m_π and $c\tau$ becomes too small to produce a LHIT or TOF signature with large efficiency. The next signature of interest is an isolated track that passes all the way through the CT but disappears before reaching the TOF and MC. The disappearing, isolated track signature is denoted by DIT. For our study, we employ the DØ detector CT radius of 73 cm (which gives greater coverage for this signal than does the CDF detector with CT radius of 130 cm). The DØ trigger logic is well adapted to this type of signal in that the CT track itself can be used to trigger the event provided it is sufficiently isolated. The isolation required by DØ for a track trigger is that no other track be in the same azimuthal wedge as the trigger track. Each azimuthal wedge is of size $\Delta\phi \sim 0.1$. The specific triggering requirements we impose are:

$$\beta_T \gamma c\tau > 73 \text{ cm}, \quad p_T^{\text{trigger}} > 11 \text{ GeV}, \quad |\eta^{\text{trigger}}| < 2, \quad \sum_{|\Delta\phi| < 0.1} p_T^{\text{tracks}} - p_T^{\text{trigger}} < 2 \text{ GeV}, \quad (8)$$

where $\Delta\phi = \phi^{\text{track}} - \phi^{\text{trigger}}$. Once the event is triggered, we require (off-line) that it have high p_T and decay before reaching the TOF device and the muon chamber. Without this latter requirement, the track would be confused with a muon, unless we impose a further requirement that it be heavily-ionizing. We hope to avoid such a requirement as it significantly reduces the signal event rate. Our specific cuts are then:

$$p_T^{\text{track}} > 30 \text{ GeV}, \quad 73 \text{ cm} < \beta \gamma c\tau < d_{\text{TOF}}, \quad E_{\text{cal}}(\Delta R < 0.4) - E_{\text{cal}}^{\tilde{\chi}_1^\pm}(\beta) \leq 2 \text{ GeV}, \quad (9)$$

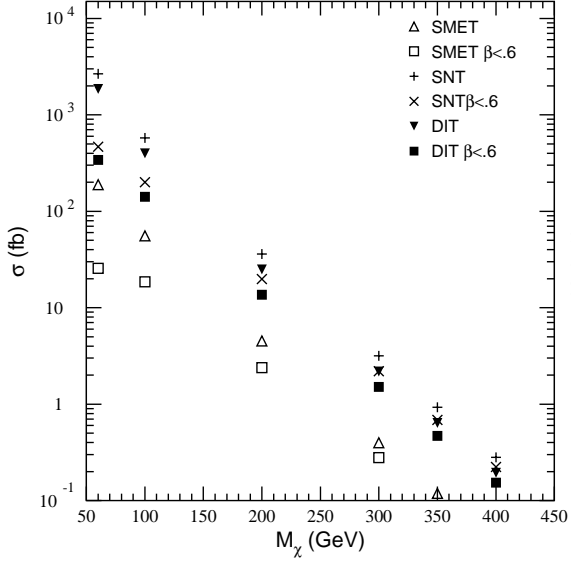
where d_{TOF} is the distance to the TOF device, e.g. to the box of the inner DØ muon chamber, $E_{\text{cal}}(\Delta R < 0.4)$ is the total energy deposited in the EC and HC calorimeters in the indicated cone surrounding the track, and $E_{\text{cal}}^{\tilde{\chi}_1^\pm}(\beta)$ is the average ionization energy that the chargino would be expected to deposit in the EC and HC calorimeters for its (measured) β in the given event, *assuming it does not decay before exiting the HC*. Given that in some events the chargino will decay soon after entering the EC, this latter cut is quite conservative. A more optimal approach when the calorimeters are sufficiently segmented in the radial direction might be to look for events with chargino ionization energy deposits in a few

inner segments but no corresponding energy deposits along the track direction in the outer segments. If the termination of the track could be seen despite the small size of the ionization energy deposits ($2 - 3$ MIP's, typically) and if “hot-spot”/ K^0/\dots backgrounds are not large, such events would be clearly distinct from background events, especially given that the trigger track must have $p_T > 30$ GeV. We have not attempted to implement this approach in our studies. In the absence of using the radial segmentation, the E_{cal} cut may be very important for eliminating backgrounds. Fortunately, it is highly efficient for the signal. Although, $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production will have the usual hadronic (initial state radiation, mini-jet, ...) activity associated with a hard scattering event, the probability of having more than 5 GeV of E_T of such activity in $|\eta| < 1$ is only about 30%, implying that small E_{cal} near the chargino, in addition to the ionization energy deposits of the chargino itself, will be automatic for most signal events. The signature defined by Eqs. (8) and (9) is called the disappearing, isolated track (DIT) signal.

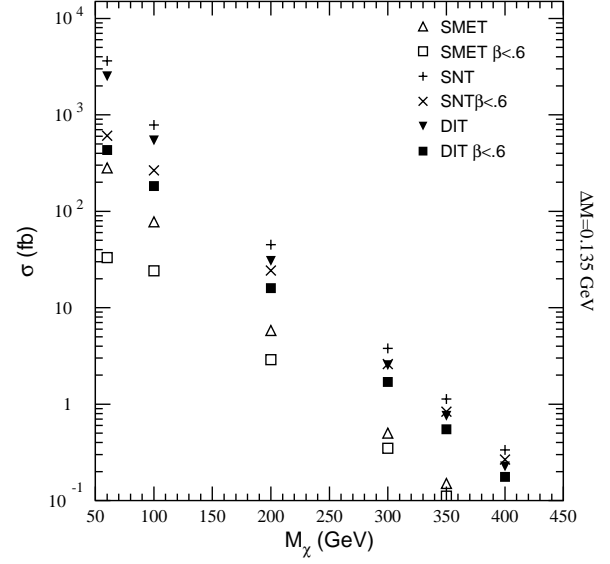
As discussed earlier, the requirements of Eq. (9) may on their own be sufficient to yield a background-free signal. In this regard, the $E_{\text{cal}}(\Delta R < 0.4)$ cut is probably critical for eliminating backgrounds. For example, an event in which a Σ^+ or Σ^- is produced and makes an isolated track in the tracker would be removed by this cut. Even if the Σ^\pm decays just outside the central tracker, its decay products are strongly interacting and will produce substantial deposits in the calorimeters, especially the hadronic calorimeter. Still, even after the $E_{\text{cal}}(\Delta R < 0.4)$ cut, one should consider the possibility that the DIT signal will not be entirely free of background. If not, one can impose a heavy-ionization requirement. The ionization of the DIT will be measured in the SVX, CT and PS. We will consider cuts requiring $\beta < 0.6$ ($\beta\gamma < 0.75$) or $\beta < 0.8$ ($\beta\gamma < 1.33$). The former is roughly equivalent to requiring 3 MIP's of ionization. As illustrated in Fig. 4, the latter is a much weaker cut that would accept many more signal events (at least for lower chargino masses), but we estimate that it would still reduce the number of background events containing 1MIP tracks by at least a factor of 10. The DIT signals with the above β cuts are denoted by DIT6 and DIT8.

Cross sections for the DIT, DIT6 and DIT8 signals are plotted as solid triangles, upside-down triangles and squares, respectively, in Figs. 5, 6 and 7. From Fig. 5, one finds that for $\Delta m_{\tilde{\chi}_1} > 125$ MeV the DIT signal is as good or better than the LHIT signal. From the $\Delta m_{\tilde{\chi}_1} = 140$ MeV window of Fig. 5, we see that even the DIT6 signal becomes superior to the LHIT and TOF signals as soon as $\Delta m_{\tilde{\chi}_1}$ exceeds m_π . Fig. 6 repeats some of the small $\Delta m_{\tilde{\chi}_1}$ DIT results, but now in comparison to the STUB and STUB+KINK signals discussed in the next section. Also shown in Fig. 6 is a $\Delta m_{\tilde{\chi}_1} = 142.5$ MeV window. One sees that the DIT signals survive crossing the $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$ decay threshold. In contrast, the LHIT and TOF cross sections are already very small at this $\Delta m_{\tilde{\chi}_1}$ value. Fig. 7 gives results for the DIT signals for still larger $\Delta m_{\tilde{\chi}_1}$ values. Assuming no background, the 95% CL reaches of the DIT and DIT6 signals are given in Fig. 12 for a range of $\Delta m_{\tilde{\chi}_1}$ values using the 3 event (no background)

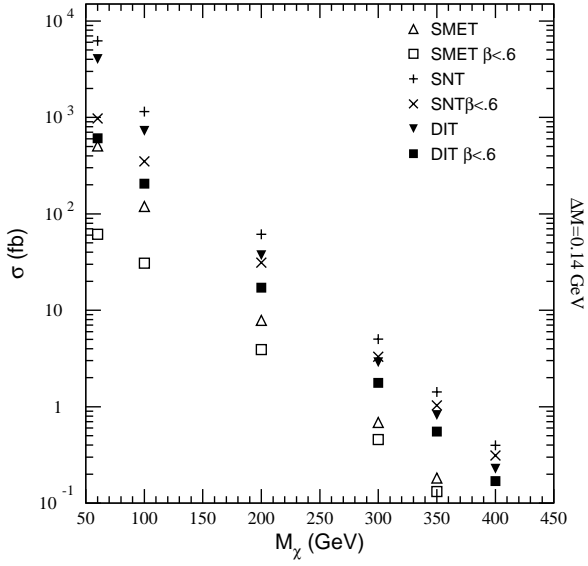
99/06/02 00.13



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99/06/02 00.13



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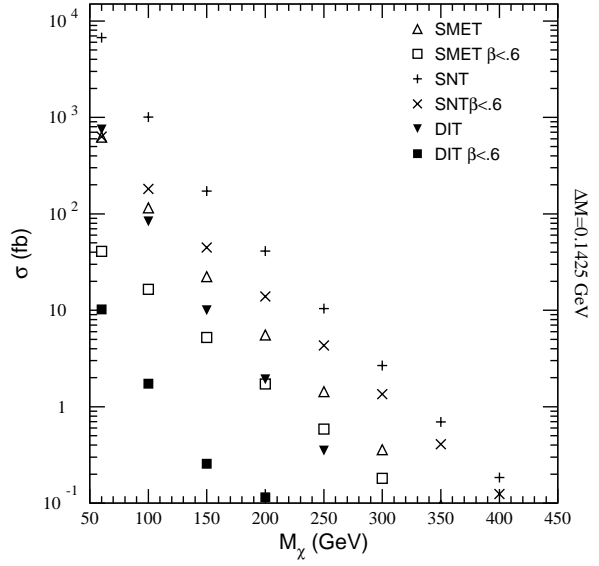


Figure 6: Cross sections for DIT and STUB “background-free” signatures at RunII: $\Delta m_{\tilde{\chi}_1} = 125, 135, 140, 142.5$ MeV.

criterion.

2.2.4 STUB and KINK signatures

As the chargino lifetime becomes still shorter, the probability for triggering an interesting event using LHIT, TOF or DIT signals becomes small. In this case, one good strategy appears to be to use the

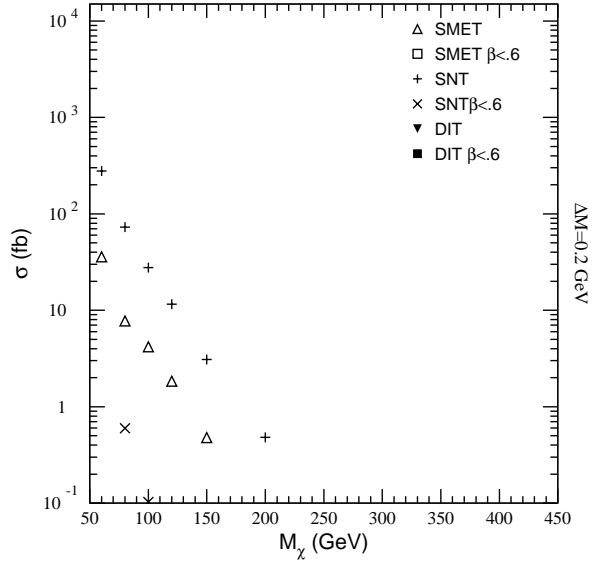
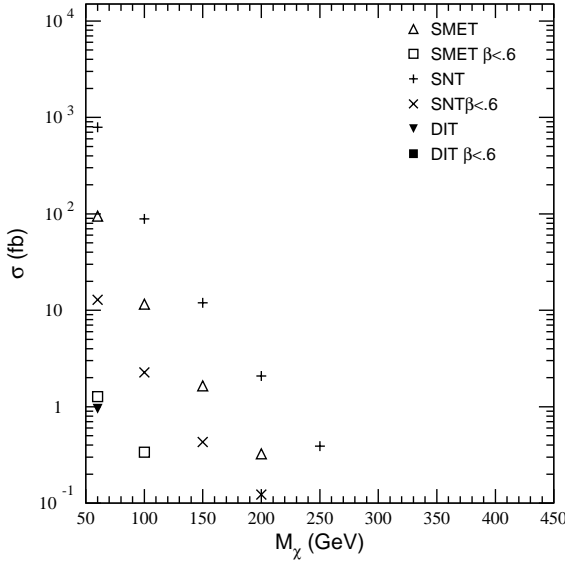
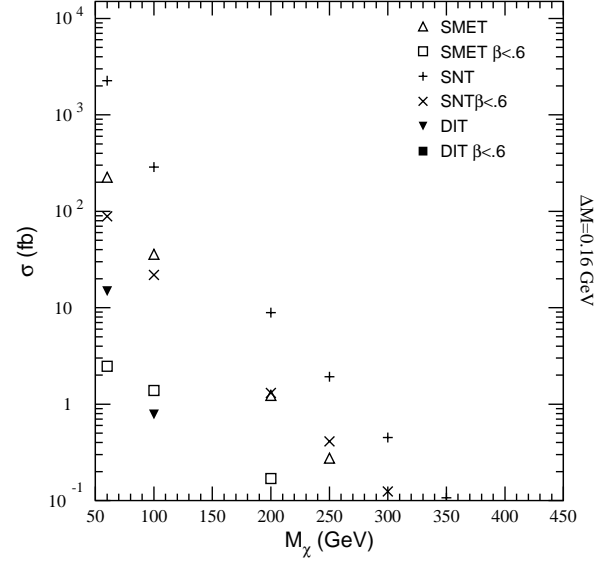
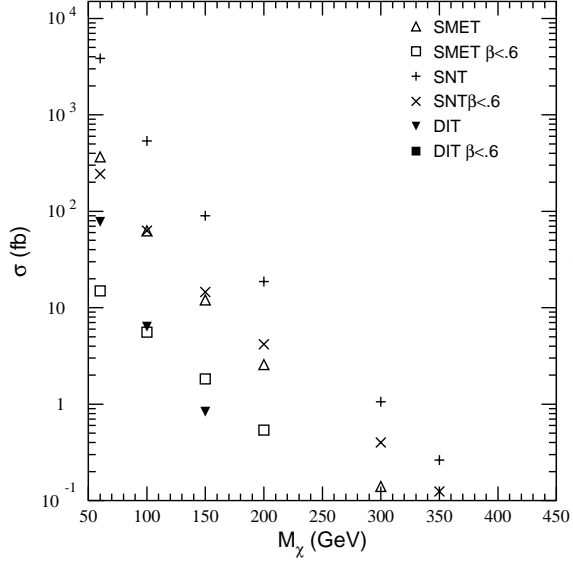


Figure 7: Cross sections for DIT and STUB “background-free” signatures at RunII: $\Delta m_{\tilde{\chi}_1} = 150, 160, 180, 200$ MeV.

\cancel{E}_T generated by initial-state-radiation of jets to trigger the event. Such jets are inevitably present in association with pair-production of massive particles at a hadron collider. In this section, we will then identify a chargino event by looking for a track that passes all the way through the SVX but disappears prior to reaching the outer radius of the central tracker, i.e. a STUB track. The $c\tau$ range of interest is thus roughly $50 \text{ cm} \gtrsim c\tau(\tilde{\chi}_1^\pm) \gtrsim \text{few cm}$. From Fig. 1 and Table 1, we observe that such $c\tau$ values are

predicted as $\Delta m_{\tilde{\chi}_1}$ ranges from just slightly above m_π up to about 190 MeV. In this $\Delta m_{\tilde{\chi}_1}$ range, the chargino decays primarily to a single soft charged pion plus the $\tilde{\chi}_1^0$. The soft pion might be visible in the tracker (where it would be emitted at substantial angle relative to the STUB track, resulting in a KINK type of signature). The neutralino takes most of the energy of the decay and is invisible. There are no calorimeter deposits associated with the STUB. Thus, interesting events can potentially be identified by demanding that the STUB be heavily-ionizing, be connected to a KINK, and/or have no associated calorimeter deposits.

For this study, we assume the detector capabilities and structure of the CDF detector, including the upgraded SVX described in Ref. [12]. We define a STUB track by the requirement that the chargino pass through all layers of the vertex detector (we assume that L00 is present) and that it have large p_T (as determined off-line using the SVX track). We also demand that there be very little calorimeter activity in a cone surrounding the STUB and that the track not make it to the end of the CT or, equivalently, to the PS. (In particular, it does not enter the calorimeters.) Our specific requirements are

$$p_T > 30 \text{ GeV}, \quad E_{\text{cal}}(\Delta R < 0.4) < 2 \text{ GeV}, \quad \beta_T \gamma c\tau > 11 \text{ cm}, \quad |\beta_z| \gamma c\tau < 45 \text{ cm}, \quad \beta \gamma c\tau < d_{\text{PS}}, \quad (10)$$

where $c\tau$ is generated for each chargino following the exponential distribution determined by the proper lifetime for the given $\Delta m_{\tilde{\chi}_1}$ value. There is some chance that a signal requiring one or more STUB's might be background free, but such events cannot be triggered on in the present CDF and DØ designs by virtue of the fact that the SVX information is not analyzed until Level-3. Still, should some sign of this scenario become apparent in RunII data, perhaps via a very weak DIT signal, an upgrade of the trigger to include this possibility might be feasible.

Additional handles are available for ensuring that a STUB signal is background free. First, one can search for the KINK created when the chargino responsible for the STUB decays to a charged pion inside the tracker. For $c\tau$ values near 11 cm, this will be very probable. We will not explicitly explore the efficiency for searching for KINK's here. However, we have computed STUB cross sections after requiring that the chargino decay a significant distance prior to reaching the outer radius of the CT. Specifically, we will give STUB cross sections for decay prior to a radial distance of 50 cm or 1.1 m. (The former is appropriate for the DØ tracker that ends at 73 cm — the latter is appropriate for the CDF tracker that extends to 1.3 m.) This type of signature will be denoted by SK (for STUB+KINK).

Finally, we have considered the additional requirement of heavy ionization deposit in the SVX. Thus, we also present results requiring ≥ 1 STUB with $\beta < 0.6$. The ≥ 3 MIP ionization of a $\beta < 0.6$ track, accompanied with the high p_T requirement and the lack of associated calorimeter activity would certainly make this a background-free signal. Note that the STUB requirement that the chargino pass through all six layers of the SVX is critical to obtaining enough dE/dx samples for a reliable determination of whether or not the track is heavily-ionizing. Samplings from just a couple of layers would not be

adequate.

Results for the cross sections obtained by requiring ≥ 1 STUB, possibly with $\beta < 0.6$ imposed, and no additional trigger (NT), are denoted by SNT and SNT6, respectively. The cross sections for these signals as a function of $m_{\tilde{\chi}_1^\pm}$ are plotted in Fig. 6 and 7 for a series of $\Delta m_{\tilde{\chi}_1} \leq 200$ MeV values. Of course, they are always larger than the DIT, DIT8 and DIT6 cross sections, and certainly remain substantial out to much larger $\Delta m_{\tilde{\chi}_1}$ values. The 95% CL limits based on 3 events (no background) are given for the SNT and SNT6 signals for a selection of $\Delta m_{\tilde{\chi}_1}$ values in Fig. 12. Very significant mass reach results for the smallest of the $\Delta m_{\tilde{\chi}_1}$ values, but the mass reach decreases significantly as $\Delta m_{\tilde{\chi}_1}$ increases. In particular, we note that for $\Delta m_{\tilde{\chi}_1} \geq 250$ GeV, only the SNT signal (and the SMET signal discussed below) have cross sections above 0.1 fb for $m_{\tilde{\chi}_1^\pm} \geq 50$ GeV. The corresponding 95% CL upper limits are shown in Fig. 12, but we do not give the corresponding cross section plots.

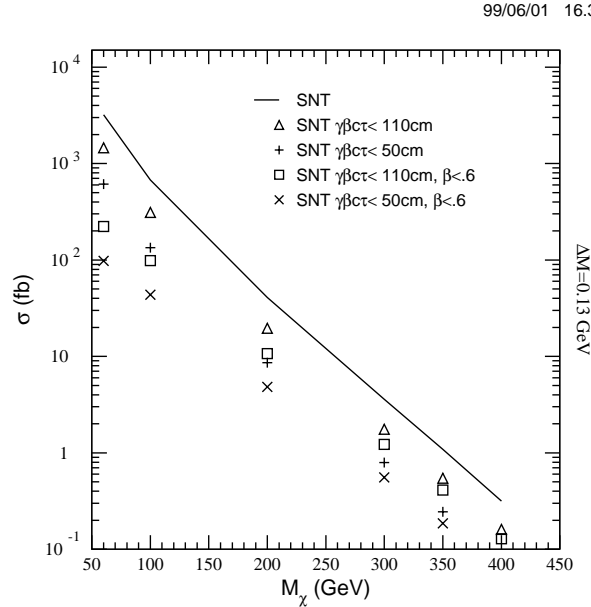


Figure 8: Cross sections for SKNT and SKNT6 signals where the KINK distance is either 50 cm, as appropriate for DØ, or 110 cm, as appropriate for CDF. The solid curve is the SNT (no β cut) cross section.

In order to assess the efficiency for seeing KINK's in association with STUB's, we present Figs. 8 and 9. In Fig. 8, we give $\Delta m_{\tilde{\chi}_1} = 130$ MeV cross sections for the 50 cm and 110 cm maximum radii (as appropriate for DØ and CDF, respectively), both before and after a $\beta < 0.6$ cut, in comparison to the full SNT cross section (no β cut). For any $\Delta m_{\tilde{\chi}_1} < m_\pi$, the relative efficiencies for these different cross sections are essentially the same. But, observation of a KINK decay for $\Delta m_{\tilde{\chi}_1} < m_\pi$ will be very difficult since the electron in the dominant $\tilde{\chi}_1^\pm \rightarrow e^\pm \nu_e \tilde{\chi}_1^0$ decay is very soft. However, once $\Delta m_{\tilde{\chi}_1} > m_\pi$ we will

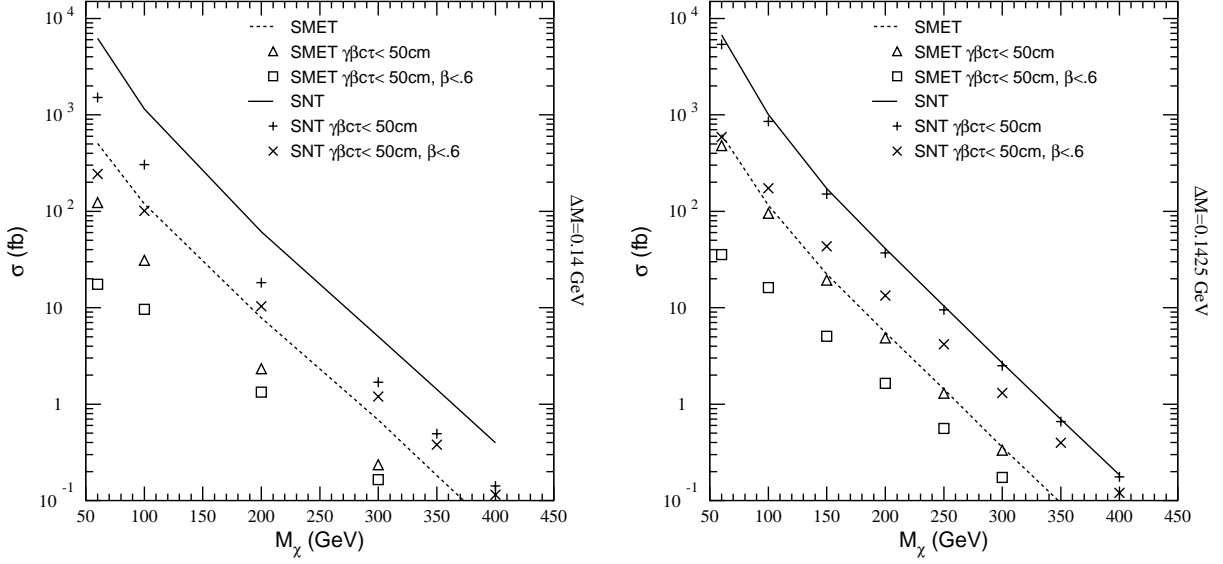


Figure 9: Cross sections for SKNT, SKNT6, SKMET and SKMET6 signals at DØ in which the K refers to the requirement that the chargino decay prior to a radial distance of 50 cm. Also shown for comparison, as the solid and dotted lines, respectively, are the SNT and SMET (no β cut) cross sections at DØ.

be looking for a somewhat harder (but still soft) charged pion daughter track. In Fig. 9, we present the SKNT and SKNT6 cross sections for the DØ KINK distance of 50 cm for $\Delta m_{\tilde{\chi}_1} = 140$ MeV and $\Delta m_{\tilde{\chi}_1} = 142.5$ MeV. We observe that the $\Delta m_{\tilde{\chi}_1} = 142.5$ MeV SNT and SKNT results are essentially the same. This is because, for $\Delta m_{\tilde{\chi}_1} > 142.5$ MeV, the $c\tau$ of the $\tilde{\chi}_1^\pm$ is sufficiently short that the decay always occurs before reaching 50 cm. Similarly, results for the CDF KINK distance of 1.1 m differ very little from the SNT results for any $\Delta m_{\tilde{\chi}_1} \geq 140$ MeV.

Unfortunately, as we have already emphasized, the above signals are not available for the current CDF and DØ trigger designs. Thus, we now consider STUB and STUB+KINK type signatures using an $\cancel{E}_T > 35$ GeV trigger for the event (\cancel{E}_T is computed assuming $|\eta| < 4$ calorimeter coverage and standard smearing and without including any SVX or tracker information). These signals will be generically denoted by SMET and SKMET. The \cancel{E}_T trigger selects events with initial state gluon radiation. We compute rates using the PYTHIA parton showering approach. For reference, the $\cancel{E}_T > 35$ GeV trigger requirement retains 8 – 13% of all $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ events. While this is not a large efficiency, it has the advantage of further reducing backgrounds from the very beginning. A photon tag trigger was also considered, but was not found to be competitive with the \cancel{E}_T trigger.

The main physics background after the trigger, but before any STUB requirements, is $Z(\rightarrow \nu\bar{\nu}) + \text{jet}$,

which has an effective cross section after our triggering requirements of $\sigma_{\text{eff}} \sim 10^3$ fb. Before STUB requirements, pure QCD backgrounds are two orders of magnitude larger than the $Z(\rightarrow \nu\bar{\nu}) + \text{jet}$ background after requiring $\cancel{E}_T > 35$ GeV, i.e. $\sigma_{\text{eff}} \sim 10^5$ fb. The requirement of an isolated, charged track reduces this background by at least a factor 10^{-3} [19]. A further requirement of ≥ 2 MIP energy deposit on all 6 SVX layers contributes another factor of $\sim 10^{-3}$. Therefore, we estimate a background cross section below about 0.1 fb. A cut of $p_T > 30$ GeV on the track may be sufficient without the 2MIP requirement. For a first estimate of sensitivity, we assume that the backgrounds are negligible after requiring one or more STUB tracks.

The cross sections for the SMET and SMET6 (i.e. $\beta < 0.6$ being required for the latter) signals are plotted as a function of $m_{\tilde{\chi}_1^\pm}$ in Figs. 6 and 7 in comparison to the DIT and DIT6 signals. The corresponding 3 event mass limits are given in Fig. 12, including results for $\Delta m_{\tilde{\chi}_1} = 250$ MeV and 300 MeV. These latter points show that only the SNT and SMET signals will give a background-free cross section for $\Delta m_{\tilde{\chi}_1}$ as large as 300 MeV.

We have also compared the SMET cross section to the cross section obtained by requiring 2 STUB's without any cut on missing energy (not plotted). One finds that the SMET efficiency is higher than that for 2 STUB's. Thus, assuming that the SMET signal is background-free, it is only if the 1 STUB, i.e. SNT, signal is also background-free that one would gain by modifying the triggering systems at CDF and DØ so that a STUB could be directly triggered on using the SVX alone.

Finally, Fig. 9 shows the SKMET and SKMET6 cross sections at DØ obtained by adding to the SMET and SMET6 cuts the requirement that the chargino decay prior to 50 cm, so that one could see in the tracker the KINK produced by the chargino decay to a soft pion. For both $\Delta m_{\tilde{\chi}_1} = 140$ MeV and 142.5 MeV, we see very little difference between these two cross sections. Thus, one could look for KINK's with little sacrifice in efficiency.

2.2.5 HIP signatures

As $\Delta m_{\tilde{\chi}_1}$ increases above 250 MeV, the chargino, on average, passes through fewer and fewer layers of the SVX. Consequently, it becomes increasingly difficult to reconstruct the SVX track and determine its p_T . In addition, the number of dE/dx samplings decreases and it becomes progressively more difficult to determine whether or not it is heavily-ionizing. The STUB signatures become very inefficient. The precise point at which the SMET and SMET6 signals (that can be implemented using current DØ and CDF trigger designs) become untenable must be determined by the experimental groups. One could be hopeful that the reach in $m_{\tilde{\chi}_1^\pm}$ of these signals might be increased for $\Delta m_{\tilde{\chi}_1} < 300$ MeV or so by looking for tracks that penetrate some, but not all, of the SVX layers. Such signals might be relatively clean if one could also see the KINK of the $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$ decay in the SVX. But, it seems very unlikely that one could go much beyond $\Delta m_{\tilde{\chi}_1} = 500$ MeV ($c\tau = 0.1$ cm). Above some point in the

$\Delta m_{\tilde{\chi}_1} = 300 - 500$ MeV range, the only visible sign of the chargino will be the high-impact-parameter of the soft charged pion emitted in $\tilde{\chi}_1^\pm$ decay. Aside from needing a means for triggering on HIP tracks, we will see that substantial additional requirements must be imposed to control the backgrounds. As a baseline for this analysis, we use the impact parameter resolution σ_b of the upgraded SVX of the CDF detector, described earlier and detailed in Ref. [12]. As before, we assume that the SVX will have the proposed, extra layer L00 at a radius of roughly 1.6 cm. If the chargino decays before this radius, we use the L00 parameterization of σ_b . Otherwise, if a decay occurs between 1.6 and 3.0 cm, we use the L0 resolution. For a pion track of $p_T = 75$ MeV, this corresponds to σ_b of .28 (.37) mm using L00 (L0); the corresponding large- p_T limits are roughly .012 (.014) mm. We require $b/\sigma_b > 5$ to eliminate fakes, which means the detector is not sensitive to $b < 0.06$ (0.07) mm. Such charged tracks, with b larger than 5 times the resolution, will be denoted as HIP's.

Unlike the STUB signature, the HIP signature has irreducible backgrounds. The best results are obtained using events that pass our $\gamma + \cancel{E}_T$ requirements. The HIP backgrounds for the monojet+ \cancel{E}_T event sample are much larger. In any hard scattering process, fragmentation and hadronization of hard jets and beam remnants can produce particles in the central rapidity region with $\gamma c\tau$ on the order of 0.1 to 10 cm that decay to charged tracks: $K_S^0, D, B, \Lambda, \Sigma, \Xi, \Omega$. To reduce this background without substantially reducing the signal, we impose a number of additional cuts:

$$75 \text{ MeV} < p_T^{\text{HIP}} < 1 \text{ GeV}, \quad E_T(\Delta R < 0.4) < 2 \text{ GeV}, \quad N_{\text{tracks}} = 1, \quad (11)$$

- The $p_T < 1$ GeV cut is not optimized. It is 100% efficient for the soft charged pions emitted in chargino decays in the models considered here, but strongly suppresses the many backgrounds that tend to yield HIP's with large p_T .
- The $p_T > 75$ MeV cut is imposed because σ_b is increasing quickly below this value.
- The $E_T(\Delta R < 0.4) < 2$ GeV cut is designed to remove HIP's directly associated with hard jets, which (by definition) have substantial transverse energy in particles nearby a $p_T < 1$ GeV HIP.
- Some background is removed by requiring that only one charged track is associated with a given impact parameter (i.e., most $K_S^0 \rightarrow \pi^+\pi^-$, $\Lambda^0 \rightarrow p^+\pi^-$, *etc.*, decays can be reconstructed and removed when one of the tracks has a large b).

Since heavy flavor is always produced in pairs from the parton sea, it may be possible to tag both hadrons and eliminate part of the background ($s\bar{s} \rightarrow \Sigma^+ K_S^0 + X$), but we have not included this in our analysis. Nor have we used the fact that some of the decays with a single charged track can be explicitly reconstructed (e.g., $\Sigma^+ \rightarrow p^+\pi^0(\rightarrow \gamma\gamma)$). After our cuts, of all the long-lived particles noted earlier, only events containing the baryons Σ^+ , Σ^- , Ξ , and Ω survive. Additional backgrounds arise

from τ decays in the processes $Z/\gamma^*(\rightarrow \tau^+\tau^-) + \gamma$ and $W(\rightarrow \tau\nu_\tau) + \gamma$, but these are insignificant after the $\gamma + \cancel{E}_T$ cuts.

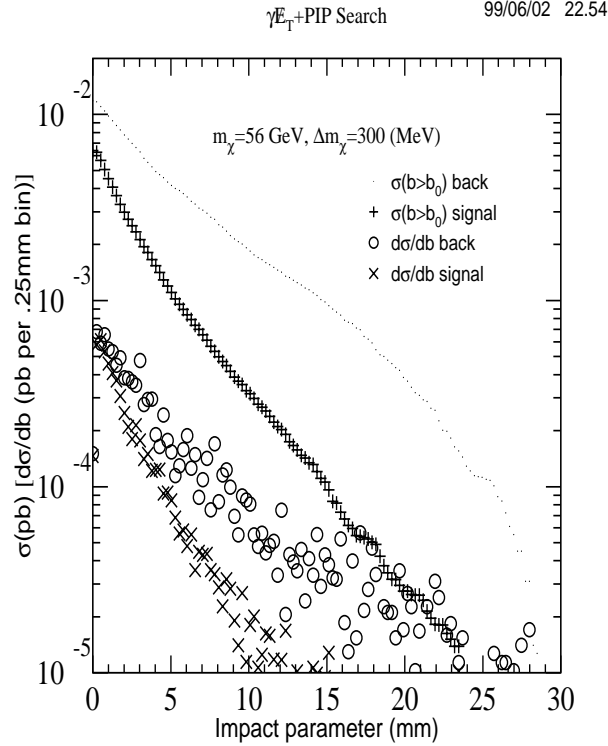


Figure 10: Impact parameter distributions for the signal and background. We plot the differential cross section, $d\sigma/db$ (in units of pb / 0.25 mm), and the integrated cross section, $\int_b^\infty (d\sigma/db')db'$ (in pb units). The signal shown here is for $m_{\tilde{\chi}_1^\pm} = 56$ GeV and $\Delta m_{\tilde{\chi}_1} = 300$ MeV. The fluctuations in the distributions are from the statistics of the Monte Carlo simulation.

After the cuts listed above, PYTHIA predicts that about 14 fb of background remains in the single HIP signal and a fraction of a fb in the double HIP signal, with a tail in the impact parameter distribution extending out to the L0 radius. For any $\Delta m_{\tilde{\chi}_1} \gtrsim 200$ MeV, the impact parameter distribution for the signal is quite similar to that for the background. This is illustrated in Fig. 10 for the case of $m_{\tilde{\chi}_1^\pm} = 56$ GeV and $\Delta m_{\tilde{\chi}_1} = 300$ MeV. As a result, no additional cuts on b appear to be useful and the HIP search is reduced to a simple counting experiment. In order to check the PYTHIA computation of the background from baryons with delayed decays that dominate the impact parameter distribution, it will be very useful to measure this same component of the impact parameter distribution in $Z(\rightarrow e^+e^-, \mu^+\mu^-) + \gamma$. This will allow considerable control of systematic errors in the background predictions.

After requiring $S/B > 0.2$, the integrated luminosity required to either exclude a chargino of a given mass at the 1.96σ (95% CL) level or discover it at the 5σ level is plotted in Fig. 11(a) or (b),

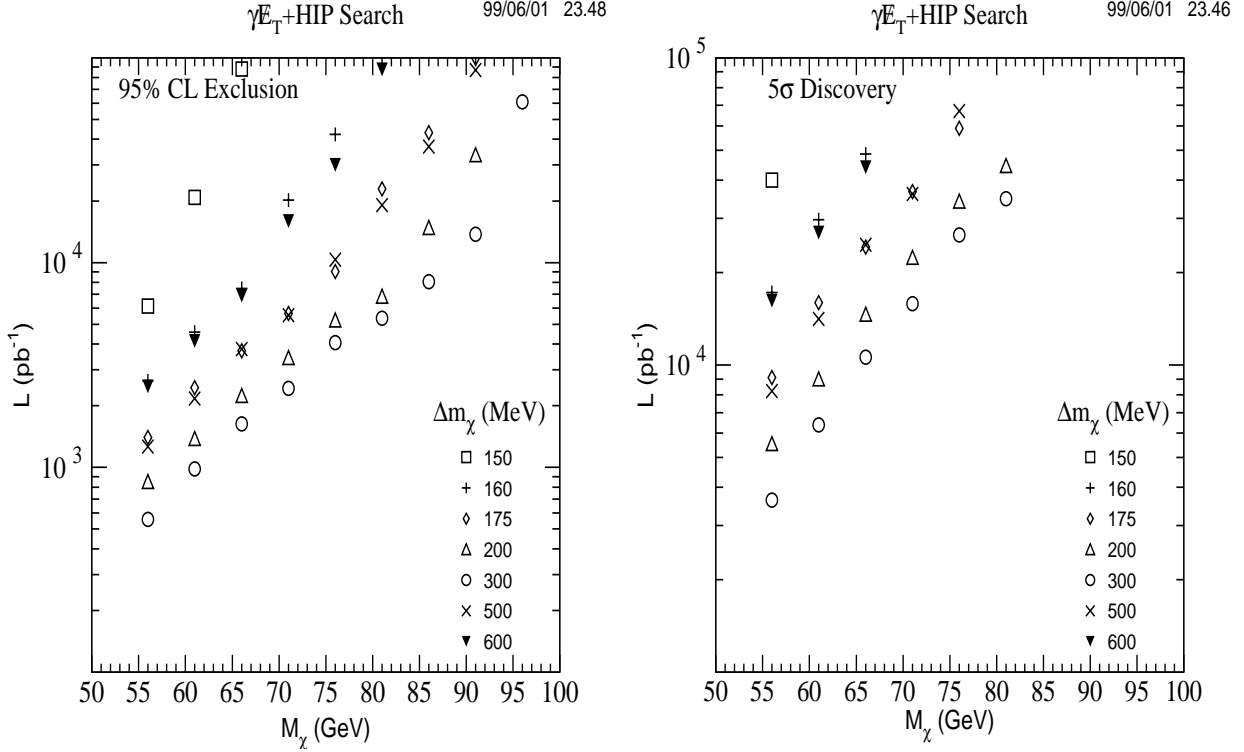


Figure 11: Reach for the $\gamma + \cancel{E}_T$ searches after requiring one or more HIP for different mass splittings $\Delta m_{\tilde{\chi}_1}$. The left curve shows the 95% C.L. exclusion; the right shows the 5σ discovery. We require $S/B > .2$ and at least 3 (5) expected events for exclusion (discovery).

respectively. For $m_{\tilde{\chi}_1^\pm}$ values above those plotted, S/B falls below the $S/B > 0.2$ criterion that we impose. We note that the HIP signal for small $\Delta m_{\tilde{\chi}_1}$ is quite weak. This is because most decays are such that the chargino passes through the SVX before decaying. In this case, one should look for the STUB and STUB+KINK signatures discussed earlier, for which backgrounds are negligible and much better sensitivity is possible. Clearly, the STUB and HIP signals are complementary with viability for the latter rising with increasing $\Delta m_{\tilde{\chi}_1}$ as mass reach for the former declines. As $\Delta m_{\tilde{\chi}_1}$ increases, the HIP+ $\gamma + \cancel{E}_T$ signal increases in viability until $\Delta m_{\tilde{\chi}_1} \gtrsim 300$ MeV. By $\Delta m_{\tilde{\chi}_1} = 600$ MeV, the typical impact parameter for the decay pion declines below $100 \mu\text{m}$, and cannot be resolved by the SVX; the HIP signal can only probe $m_{\tilde{\chi}_1^\pm}$ values below the roughly 90 GeV limit set by the DELPHI analysis for $\Delta m_{\tilde{\chi}_1} \geq 600$ GeV.

Some further discussion of the difference between the STUB and HIP signals is perhaps useful. First, it is the large background that restricts the mass reach of the HIP signal, whereas the biggest limitation on the STUB signals is associated with the chargino lifetime. Second, the STUB signals are background-free while the HIP signal is not. The key to eliminating backgrounds to STUB signatures is

that the Σ^\pm, \dots hadrons that can give an SVX track will decay to particles that pass all the way through the CT and give sizeable hadronic calorimeter energy deposits; in addition, one or more of the decay products are normally (i.e. except for distribution tails where the charged decay products all have small p_T) visible as a full CT track. If there is some remaining background, then one would have to also look to see if the STUB is heavily-ionizing. The Σ^\pm, \dots background tracks would all be minimal-ionizing, so that a $\beta < 0.6$ requirement would certainly eliminate the remaining background. The cross-over point between the signals depends on whether the heavy-ionization requirement is necessary to remove the background. For $\Delta m_{\tilde{\chi}_1} = 180$ MeV, Fig. 12 shows that with $L = 30 \text{ fb}^{-1}$, the SMET (SMET6) signals (which include the $\cancel{E}_T > 35$ GeV trigger requirement) can be used to exclude at 95% CL any $m_{\tilde{\chi}_1^\pm} \lesssim 240$ GeV ($\lesssim 140$ GeV). In contrast, for $\Delta m_{\tilde{\chi}_1} = 180$ MeV the HIP signal can only probe $m_{\tilde{\chi}_1^\pm} \lesssim 80$ GeV. For $\Delta m_{\tilde{\chi}_1} = 200$ MeV, the SMET signal still probes up to $m_{\tilde{\chi}_1^\pm} \lesssim 190$ GeV, but the SMET6 signal falls just below the 95% CL. For $\Delta m_{\tilde{\chi}_1} = 300$ MeV, the SMET and HIP signals both probe up to $m_{\tilde{\chi}_1^\pm} \lesssim 90$ GeV.

Various exotic signals can be envisioned that might probe $\Delta m_{\tilde{\chi}_1}$ values above 600 MeV, but we only comment on them here. For example, if $\Delta m_{\tilde{\chi}_1} > m_s + m_c$ the decay $\tilde{\chi}_1^\pm \rightarrow D_s^* \tilde{\chi}_1^0$ may occur, leading to a D_s meson that carries most of the D_s^* 's momentum. When combined with an \cancel{E}_T trigger, the signature would be quite distinctive since the D_s will not be associated with a jet. However, the event rate for such an “exclusive” channel might be small.

3 Summary of Results and Discussion

In the previous sections, we considered several signatures for chargino production in models with near mass degeneracy between the lightest chargino and neutralino. A brief summary of these signatures appears in Table 3. We have seen that there is a natural boundary near a mass splitting of $\Delta m_{\tilde{\chi}_1} \sim 300$ MeV.

- For values of $\Delta m_{\tilde{\chi}_1} \lesssim 300$ MeV (mass region A), one considers a set of signals based on observing a long-lived chargino as a semi-stable, isolated track in the detector. The most unique signals are the long, heavily-ionizing-track (LHIT) signal and the delayed time-of-flight (TOF) signal. These are present for events in which the chargino does not decay before reaching the muon chambers. For events in which the chargino decays before the muon chambers, but still produces a track of substantial length, the relevant signals are the disappearing-isolated-track (DIT) signal and the short-isolated-SVX-track (STUB) signal. The LHIT and TOF signals are dominant if $\Delta m_{\tilde{\chi}_1}$ is very small (implying a very long chargino lifetime), but the latter signals quickly turn on as $\Delta m_{\tilde{\chi}_1}$ is increased, becoming the primary signals as $\Delta m_{\tilde{\chi}_1}$ is increased to values above m_π .

All these signals are distinct enough to be possibly background-free. Because of the subtle nature of these signals, in estimating the the range of $m_{\tilde{\chi}_1^\pm}$ values to which they can be sensitive for any given $\Delta m_{\tilde{\chi}_1}$, we have imposed cuts/requirements such that the backgrounds should be negligible, even at the expense of some signal rate.

- For $\Delta m_{\tilde{\chi}_1} \gtrsim 300$ MeV, the chargino has an average lifetime such that the background-free signals have too low an event rate (at the Tevatron) and we are forced to consider signals with substantial backgrounds from physics and mismeasurement sources. There are two primary signals in this latter category, but the most sensitive one can only be used for $300 \text{ MeV} \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 600 \text{ MeV}$ (mass region B). It relies on observation of a high-impact-parameter (HIP) pion from the chargino decay in association with a photon tag/trigger and large \cancel{E}_T . For $600 \text{ MeV} \lesssim 10 - 20 \text{ GeV}$ (mass region C), the chargino decay is essentially prompt, and we are forced to use the very insensitive signal of a photon tag/trigger plus large \cancel{E}_T to search for chargino production.

We will now summarize the Tevatron mass reach in $m_{\tilde{\chi}_1^\pm}$ that can be achieved in the $M_2 < M_1 \ll |\mu|$ scenario (1), assuming that the gluino, squarks and sleptons are all too heavy to have significant production rate (as is entirely possible).

Region (A) For $\Delta m_{\tilde{\chi}_1}$ values $\lesssim 200 - 300$ MeV, one considers the background-free signals summarized above, which will have the most substantial mass reach in $m_{\tilde{\chi}_1^\pm}$. The $L = 2 \text{ fb}^{-1}$ and $L = 30 \text{ fb}^{-1}$ 95% CL (3 events, no background) limits on $m_{\tilde{\chi}_1^\pm}$ deriving from these signals are summarized in Fig. 12. We give a brief verbal summary.

- $\Delta m_{\tilde{\chi}_1} < m_\pi$:

For such $\Delta m_{\tilde{\chi}_1}$, the average $c\tau$ of the chargino is of order a meter or more. The LHIT and TOF signals are prominent, but the DIT and STUB signals appear if $\Delta m_{\tilde{\chi}_1}$ is not extremely small. These arise as a result of the exponential form of the $c\tau$ distribution in the chargino rest frame, which implies that the chargino will decay over a range of radii within the detector. One must also include the event-by-event variation of the boosts imparted to the chargino(s) during production.

- The LHIT signature can probe masses in the range $260 - 325$ ($380 - 425$) GeV for $L = 2 \text{ fb}^{-1}$ (30 fb^{-1}), the lower reach applying for $\Delta m_{\tilde{\chi}_1} \sim m_\pi$ and the highest reach applying for any $\Delta m_{\tilde{\chi}_1} \lesssim 125$ MeV. The reach of the TOF signature is nearly identical to that of the LHIT signature.⁵

⁵The primary difference between the LHIT and TOF signals is that the LHIT signal requires $\beta\gamma < 0.85$ for heavy ionization, whereas the effective cut-off on $\beta\gamma$ imposed by the TOF delay requirement allows much larger $\beta\gamma$ to also contribute. That the maximum reach of the two signals is essentially the same is somewhat accidental. It happens that

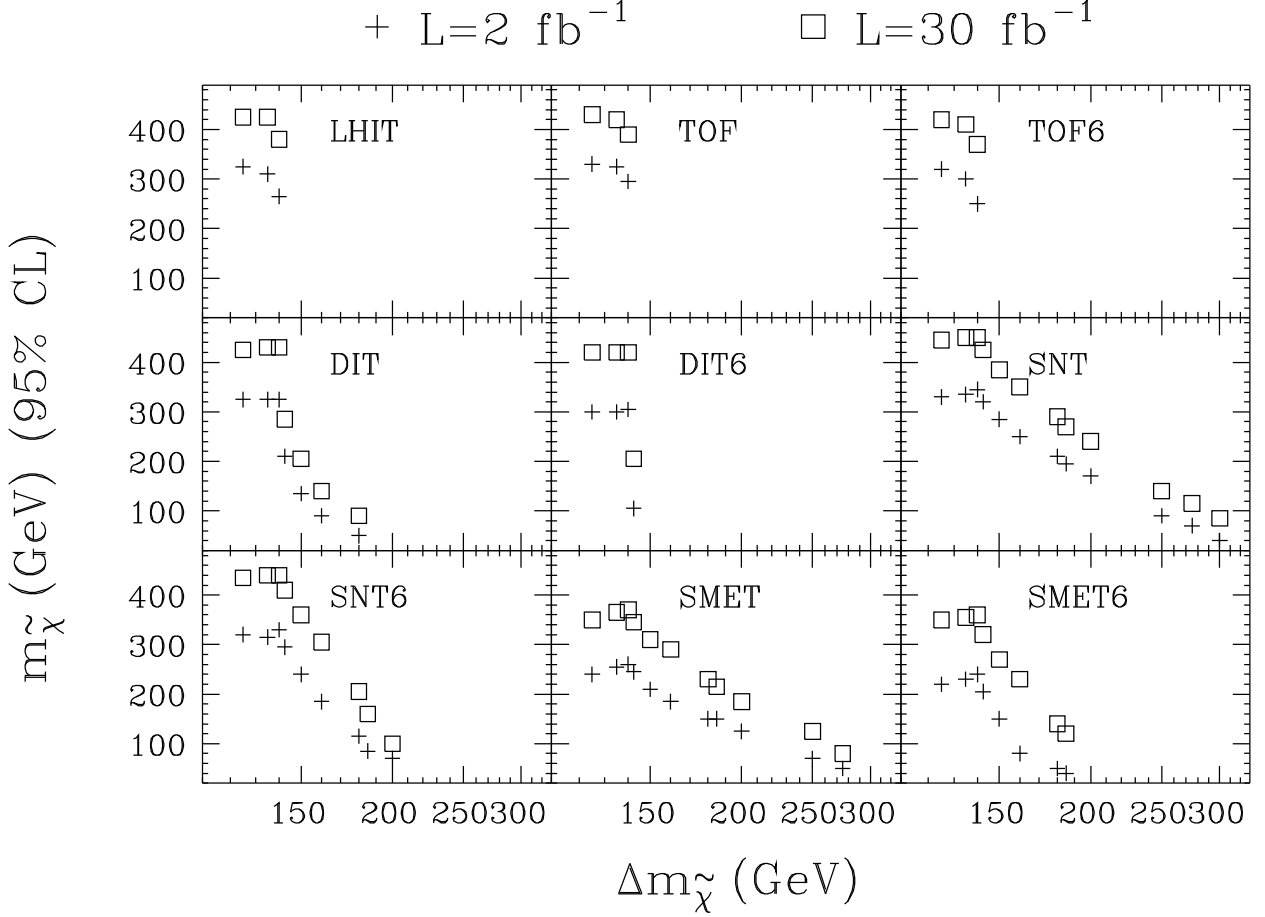


Figure 12: 95% CL lower limits on $m_{\tilde{\chi}_1^\pm}$ as a function of $\Delta m_{\tilde{\chi}_1}$ for “background-free” signatures at RunII with $L = 2 \text{ fb}^{-1}$ and $L = 30 \text{ fb}^{-1}$.

- The DIT signature has a reach of 320 (425) GeV for $120 \text{ MeV} \leq \Delta m_{\tilde{\chi}_1} \leq m_\pi$,⁶ and, in particular, is more efficient than the LHIT and TOF signals for $\Delta m_{\tilde{\chi}_1} \sim m_\pi$. The DIT signature reach drops by about 20 GeV with a $\beta < 0.6$ cut (DIT6) designed to require that the chargino track be heavily-ionizing.
- The STUB signature with no additional trigger (SNT) can reach to $\simeq 340$ (450) GeV for $120 \text{ MeV} \leq \Delta m_{\tilde{\chi}_1} \leq m_\pi$, which mass reach drops by 10 – 20 GeV if $\beta < 0.6$ is required.

the chargino production cross sections are large enough that charginos with rather large mass can be probed and such massive charginos are produced with low β . Thus, a cut requiring low β is highly efficient. This is illustrated, for example, by comparing the TOF to the TOF6 results in Fig. 12. This same accident is generic to all the signals discussed, so long as $\Delta m_{\tilde{\chi}_1} < m_\pi$.

⁶We did not study lower $\Delta m_{\tilde{\chi}_1}$ values since they are highly improbable after including radiative correction contributions to $\Delta m_{\tilde{\chi}_1}$.

However, neither DØ nor CDF can use STUB information at Level-1 in their current design.

- With the addition of a standard \cancel{E}_T trigger, the resulting STUB signature (SMET) will be viable with the present detectors, reaching to 240 – 260 (350 – 375) GeV for $120 \text{ MeV} \leq \Delta m_{\tilde{\chi}_1} \leq m_\pi$, which numbers drop by about 10 GeV if $\beta < 0.6$ is required (SMET6).

- $m_\pi \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 200 - 300 \text{ MeV}$:

- The LHIT and TOF signatures disappear, since almost all produced charginos decay before reaching the MC or TOF.
- The DIT signature remains as long as the $\beta < 0.6$ (heavily-ionizing) requirement is not necessary to eliminate backgrounds. If we require $\beta < 0.6$, there is a mismatch with the requirement that the chargino pass through the CT – once $\Delta m_{\tilde{\chi}_1}$ is above 145 MeV, the entire signal is generated by large boosts in the production process which is in conflict with requiring small β .
- The SNT signature probes $m_{\tilde{\chi}_1^\pm} \lesssim 300 \text{ GeV}$ ($\lesssim 400 \text{ GeV}$) for $\Delta m_{\tilde{\chi}_1} \sim m_\pi$ and $L = 2 \text{ fb}^{-1}$ ($L = 30 \text{ fb}^{-1}$). For $\Delta m_{\tilde{\chi}_1}$ as large as 300 MeV, it alone among the background-free channels remains viable, probing $m_{\tilde{\chi}_1^\pm} \lesssim 70 \text{ GeV}$ ($\lesssim 95 \text{ GeV}$). Certainly, it would extend the $\sim 90 \text{ GeV}$ limit obtained by DELPHI at LEP2 that applies for $\Delta m_{\tilde{\chi}_1} < 200 \text{ MeV}$ and the $\sim 45 \text{ GeV}$ limit from LEP data that is the only available limit for $200 \text{ MeV} \leq \Delta m_{\tilde{\chi}_1} \leq 300 \text{ MeV}$. But, as stated above, the SNT signature will not be possible without a Level-1 SVX trigger.
- The STUB+ \cancel{E}_T , SMET and SMET6 signatures are fully implementable at RunII and have a reach that is only about 20 GeV lower than their SNT and SNT6 counterparts.

Region (B) For $300 \text{ MeV} \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 600 \text{ MeV}$, the high-impact-parameter (HIP) signal (a $\gamma + \cancel{E}_T$ tag for events yields the smallest backgrounds) is very useful despite the large background from production of Σ^\pm, \dots hadrons. It would yield a 95% CL lower bound of 95 GeV (75 GeV) on $m_{\tilde{\chi}_1^\pm}$ for $\Delta m_{\tilde{\chi}_1} = 300 \text{ MeV}$ ($\Delta m_{\tilde{\chi}_1} = 600 \text{ MeV}$) for $L = 30 \text{ fb}^{-1}$. This would represent some improvement over the $\sim 60 \text{ GeV}$ lower bound obtained in the current DELPHI analysis of their LEP2 data for this same range of $\Delta m_{\tilde{\chi}_1}$ if the sneutrino is heavy. (If the $\tilde{\nu}$ is light, then there is no useful LEP2 limit if $300 \text{ MeV} \leq \Delta m_{\tilde{\chi}_1} \leq 500 \text{ MeV}$, but LEP data requires $m_{\tilde{\chi}_1^\pm} > 45 \text{ GeV}$.) With only $L = 2 \text{ fb}^{-1}$ of data, the HIP analysis would only exclude $m_{\tilde{\chi}_1^\pm} < 68 \text{ GeV}$ ($< 53 \text{ GeV}$) for $\Delta m_{\tilde{\chi}_1} = 300 \text{ MeV}$ ($\Delta m_{\tilde{\chi}_1} = 600 \text{ MeV}$).

Region (C) For $\Delta m_{\tilde{\chi}_1} \gtrsim 600 \text{ MeV}$, up to some fairly large value (we estimate at least 10 to 20 GeV), the chargino decay products are effectively invisible at a hadron collider and the most useful signal is $\gamma + \cancel{E}_T$. However, this signal at best probes $m_{\tilde{\chi}_1^\pm} \lesssim 60 \text{ GeV}$ (for any $L > 2 \text{ fb}^{-1}$), whereas the DELPHI

analysis of their LEP2 data already excludes $m_{\tilde{\chi}_1^\pm} \leq 60$ GeV for $500 \text{ MeV} \leq \Delta m_{\tilde{\chi}_1} \leq 3$ GeV (if the sneutrino is heavy — only ≤ 48 GeV if the sneutrino is light) and $m_{\tilde{\chi}_1^\pm} \leq 90$ GeV for $\Delta m_{\tilde{\chi}_1} > 3$ GeV.

All the above mass limits assume that the gluino is quite heavy and rarely produced at the Tevatron. If it is not too much heavier than the chargino, then all the above signals will have additional event rate coming from $\tilde{g}\tilde{g}$ pair production followed by $\tilde{g} \rightarrow \tilde{\chi}_1^\pm q'\bar{q}$ decays. The effect of $\tilde{g}\tilde{g}$ pair production on the LHIT, TOF, DIT, SNT, SMET, and HIP signatures depends strongly on the mass splitting between the gluino and the chargino as well as on $\Delta m_{\tilde{\chi}_1}$, so we did not explicitly consider possible enhancements to these signatures here. Instead, we focused on the fact that gluino production will provide a critical increase in the mass reach when neither the chargino track nor its decay products are visible, and the only signatures are those dependent primarily upon missing transverse energy. This is the case if $\Delta m_{\tilde{\chi}_1}$ is above 600 MeV but below the point at which the chargino decay products can be seen as energetic jets or leptons. For example, we explicitly considered the extreme of $m_{\tilde{g}} \sim m_{\tilde{\chi}_1^\pm}$ (which is quite natural in some string models — see introduction). In this case, we found that a monojet+ \cancel{E}_T signal will probe (at 95% CL) $m_{\tilde{g}} \sim m_{\tilde{\chi}_1^\pm} < 150$ GeV, while the $\gamma + \cancel{E}_T$ signal will probe $m_{\tilde{g}} \sim m_{\tilde{\chi}_1^\pm} < 175$ GeV. (Both numbers assume that $S/B > 0.2$ is required for a viable signal in the presence of large background.)

Finally, we wish to note that the precise values of $m_{\tilde{\chi}_1^\pm}$ and $\Delta m_{\tilde{\chi}_1}$ will be of significant theoretical interest. $m_{\tilde{\chi}_1^\pm}$ will be determined on an event-by-event basis if the chargino's momentum and velocity can both be measured. For the LHIT signal, p will be measured by the curvature of the track in the SVX and in the CT. The velocity will be measured by the ionization energy deposit in the SVX, CT and PS. In the case of the TOF signal, there will be, in addition, an independent time-of-flight determination of β . For the DIT signal, the SVX+CT curvatures give a measurement of p and the SVX+CT+PS ionization energy deposits provide a determination of β . For the SNT and SMET signals, p and β are measured by curvature and ionization (respectively) in the SVX. (Note that, in all these cases, accepting only events roughly consistent with a given value of $m_{\tilde{\chi}_1^\pm}$ will provide further discrimination against backgrounds.) However, for the HIP and $\gamma + \cancel{E}_T$ signals $m_{\tilde{\chi}_1^\pm}$ can only be estimated from the absolute event rate. As regards $\Delta m_{\tilde{\chi}_1}$, it will be strongly constrained by knowing which signals are present and their relative rates. In addition, if the soft charged pion can be detected, its momentum distribution, in particular the end-point thereof, would provide an almost direct determination of $\Delta m_{\tilde{\chi}_1}$.

4 Conclusion

We have examined well-motivated scenarios of soft-SUSY-breaking with high-scale boundary conditions that lead to a lightest chargino and a lightest neutralino which are both wino-like and nearly degenerate in mass. While it is not necessary, the gluino can also be nearly degenerate with the $\tilde{\chi}_1^\pm$

and $\tilde{\chi}_1^0$. Typical values of the mass splitting $\Delta m_{\tilde{\chi}_1} \equiv m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ in such models range from $\lesssim m_\pi$ to several GeV. If squarks, sleptons, and sneutrinos are heavy (as is quite possible), then the signals for supersymmetry at the Tevatron will be very limited and very strongly-dependent upon the precise value of $\Delta m_{\tilde{\chi}_1}$. In the very worst case, the gluino could also be heavy and the only substantial SUSY production cross sections would be those for $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$. The mSUGRA-motivated tri-lepton signal from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production is suppressed, because $\tilde{\chi}_2^0$ has a small wino component and because $\tilde{\chi}_1^\pm$ typically has a very small semi-leptonic branching ratio (for $\Delta m_{\tilde{\chi}_1} < m_\pi$ the branching ratio can be large, but the lepton would be very soft; for $\Delta m_{\tilde{\chi}_1} \geq m_\pi$, the dominant decay is $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$ until $\Delta m_{\tilde{\chi}_1} > 1$ GeV). The signatures that can be used to search for the $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production processes are summarized in Table 3, given earlier in the paper. We give a very brief summary of the results.

If $\Delta m_{\tilde{\chi}_1}$ is sufficiently small that the $c\tau$ for chargino decay is of order cm's or greater, then a promising signature is an isolated (chargino) track of significant length, that possibly either penetrates to the muon chambers or suddenly disappears after appearing in the silicon vertex detector and/or central tracker. The chargino track will not leave hadronic energy deposits and will have a low-velocity, heavily-ionizing nature for many events. In this case, one or more background-free signals will be viable, allowing sensitivity to chargino masses competitive with, or in many cases much superior to, those that can be probed for mSUGRA boundary conditions. The importance of particular detector components and triggers for such signatures, as outlined in the main body of this paper, should be carefully reviewed by the CDF and DØ collaborations. The silicon tracker (SVX), central tracking system (CT), pre-shower (PS), electromagnetic and hadronic calorimeters (EC and HC), time-of-flight (TOF) measurement and muon chambers (MC) all play crucial roles that change as a function of $\Delta m_{\tilde{\chi}_1}$. (Our detector notation is summarized in Table 2.)

If $\Delta m_{\tilde{\chi}_1} \gtrsim 300$ MeV, the only available signals have substantial backgrounds. For $300 \text{ MeV} \lesssim \Delta m_{\tilde{\chi}_1} \lesssim 600$ MeV, the $c\tau$ of the chargino decay is such that most events contain at least one high-impact-parameter (HIP) pion track (the pion coming from the decay of the chargino). These HIP's can be observed above the backgrounds provided that a radiated photon is present to tag the \cancel{E}_T . The HIP signature will probe up to $m_{\tilde{\chi}_1^\pm} \sim 95 - 75$ GeV for $L = 30 \text{ fb}^{-1}$ ($\sim 68 - 53$ for $L = 2 \text{ fb}^{-1}$). The $L = 30 \text{ fb}^{-1}$ limits represent some improvement over the DELPHI analysis based on LEP2 data, which currently excludes $m_{\tilde{\chi}_1^\pm} \lesssim 60$ GeV in this same mass range. For $\Delta m_{\tilde{\chi}_1} \gtrsim 600$ MeV, the chargino decay will be effectively prompt, and the main decay modes will be $\ell \nu \tilde{\chi}_1^0$ and $q' \bar{q} \tilde{\chi}_1^0$. If $\Delta m_{\tilde{\chi}_1}$ is at the same time too small for the jets or leptons coming from the chargino decays to be observable, then the best limits on $m_{\tilde{\chi}_1^\pm}$ will come from the $\gamma + \cancel{E}_T$ channel. The mass reach in $m_{\tilde{\chi}_1^\pm}$ will not exceed about 60 GeV. This is about the same as the DELPHI limit for $600 \text{ MeV} \leq \Delta m_{\tilde{\chi}_1} \leq 3 \text{ GeV}$ but is substantially below the DELPHI limit of ~ 90 GeV that applies for $\Delta m_{\tilde{\chi}_1} > 3 \text{ GeV}$. In short, it is clear that a value of $\Delta m_{\tilde{\chi}_1} \geq 300$ MeV is both challenging and a real possibility.

| $\Delta m_{\tilde{\chi}_1}$ (MeV) | $c\tau$ (cm) | Best RunII signature(s) | Trigger | Crucial measurements and associated detector components | Reach (GeV) |
|--------------------------------------|-----------------|----------------------------|------------------------|---|----------------|
| 0 | ∞ | TOF | MC | TOF, p_T (SVX+CT) | 460 |
| | | LHIT | MC | p_T (SVX+CT), dE/dx (SVX+CT+PS) | 450 |
| 125 | 1155 | TOF | MC | TOF, p_T (SVX+CT) | 430 |
| | | LHIT | MC | p_T (SVX+CT), dE/dx (SVX+CT+PS) | 425 |
| | | DIT | CT | p_T (SVX+CT), HC veto | 425 |
| | | DIT6 | CT | same + dE/dx (SVX+CT+PS), | 420 |
| 135 | 754 | LHIT | MC | p_T (SVX+CT), dE/dx (SVX+CT+PS) | 425 |
| | | TOF | MC | TOF, p_T (SVX+CT) | 420 |
| | | DIT | CT | p_T (SVX+CT), HC veto | 430 |
| | | DIT6 | CT | same + dE/dx (SVX+CT+PS) | 420 |
| 140 | 317 | DIT | CT | p_T (SVX+CT), HC veto | 430 |
| | | DIT6 | CT | same + dE/dx (SVX+CT+PS) | 420 |
| 142.5 | 24 | SMET | \cancel{E}_T | p_T (SVX), PS+EC+HC veto | 345 |
| | | SMET6 | \cancel{E}_T | same + dE/dx (SVX) | 320 |
| 150 | 11 | SMET | \cancel{E}_T | p_T (SVX), PS+EC+HC veto | 310 |
| | | SMET6 | \cancel{E}_T | same + dE/dx (SVX) | 270 |
| 185 | 3.3 | SMET | \cancel{E}_T | p_T (SVX), PS+EC+HC veto | 215 |
| | | SMET6 | \cancel{E}_T | same + dE/dx (SVX) | 120 |
| 200 | 2.4 | SMET | \cancel{E}_T | p_T (SVX), PS+EC+HC veto | 185 |
| 250 | 1.0 | SMET | \cancel{E}_T | p_T (SVX), PS+EC+HC veto | 125 |
| 300 | 0.56 | HIP | γ, \cancel{E}_T | b^π (SVX,L0), $p_T^\gamma, \cancel{E}_T, p_T^\pi$ (CT), EC+HC veto | 95 |
| 600 | 0.055 | HIP | γ, \cancel{E}_T | b^π (SVX,L00), $p_T^\gamma, \cancel{E}_T, p_T^\pi$ (CT), EC+HC veto | 75 |
| 750-? | ~ 0 | $\gamma + \cancel{E}_T$ | γ, \cancel{E}_T | p_T^γ, \cancel{E}_T | < 60 |

Table 4: Summary of the best signals at RunII for $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production and important detector components and measurements as a function of $\Delta m_{\tilde{\chi}_1}$. Mass reaches quoted are 95% CL for $L = 30 \text{ fb}^{-1}$. Detector component notation is summarized in Table 2. Signal definitions are summarized in Table 3. The PS, EC, or HC veto requires no preshower, small EC, or small HC energy deposits in a $\Delta R < 0.4$ cone around the $\tilde{\chi}_1^\pm$ track candidate. p_T (p_T^π) is the p_T of the $\tilde{\chi}_1^\pm$ (π^\pm from $\tilde{\chi}_1^\pm \rightarrow \pi^\pm \tilde{\chi}_1^0$). b^π is the π^\pm impact parameter.

An overall summary of the signals and their mass reach at the Tevatron for detecting $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$ production in the $M_2 < M_1 \ll |\mu|$ scenario (1) appears in Table 4.

Mass reach in $m_{\tilde{\chi}_1^\pm}$ is significantly improved if the gluino mass is not so large that $\tilde{g}\tilde{g}$ production is suppressed. In particular, we considered the other extreme of $m_{\tilde{g}} \sim m_{\tilde{\chi}_1^\pm}$, as motivated in some of the models for which the lightest chargino and neutralino are both wino-like. In this case, we found that the $\gamma + \cancel{E}_T$ signal will probe $m_{\tilde{g}} \sim m_{\tilde{\chi}_1^\pm}$ values as large as ~ 175 GeV (for $L \geq 2 \text{ fb}^{-1}$ at the Tevatron), while a monojet+ \cancel{E}_T signature can probe up to ~ 150 GeV.

In some of the models in question, it is entirely possible that $\Delta m_{\tilde{\chi}_1}$ is quite substantial (> 20 GeV). The mass reach that can be achieved in this case requires further study. The signals considered in this paper are not very useful. If the gluino is heavy, then one should explore the potential of the tri-lepton signal coming from $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production. However, this is a suppressed cross section when both the lightest neutralino and lightest chargino are wino-like. Standard mSUGRA studies do not apply without modification; the cross section must be rescaled and the lepton acceptance recalculated as a function of $\Delta m_{\tilde{\chi}_1}$. If the gluino is close in mass to the chargino, then the standard multi-jet+ \cancel{E}_T signal will be viable when $\Delta m_{\tilde{\chi}_1}$ is large enough for the jets in $\tilde{\chi}_1^\pm \rightarrow q'\bar{q}\tilde{\chi}_1^0$ decay to be visible. The like-sign di-lepton signal will also emerge for large $\Delta m_{\tilde{\chi}_1}$, as the leptons in $\tilde{\chi}_1^\pm \rightarrow \ell\nu\tilde{\chi}_1^0$ become energetic. Since both signals will have substantial backgrounds, a detailed study is required to determine their exact mass reach as a function of $\Delta m_{\tilde{\chi}_1}$. If the gluino has a moderate mass but $m_{\tilde{g}} - m_{\tilde{\chi}_1^\pm}$ is large enough, then the extra jets from $\tilde{g} \rightarrow q'\bar{q}\tilde{\chi}_1^\pm$ become visible and nearly all events contain more than one jet. The multi-jet+ \cancel{E}_T signal becomes viable as shown in Ref. [4]. (We note that the reach of the monojet+ \cancel{E}_T signature explored here deteriorates once the multi-jet+ \cancel{E}_T signal becomes substantial. For instance, we find that the former signal is no longer useful once $m_{\tilde{g}} - m_{\tilde{\chi}_1^\pm} > 10$ GeV.)

Of course, additional SUSY signals will emerge if some of the squarks, sleptons and/or sneutrinos are light enough (but still heavier than the $\tilde{\chi}_1^\pm$) that their production rates are substantial. In particular, leptonic signals from the decays [*e.g.* $\tilde{\ell}_L^\pm \rightarrow \ell^\pm \tilde{\chi}_1^0$ or $\tilde{\nu}_\ell \rightarrow \ell^\pm \tilde{\chi}_1^\mp$ in scenario (1)] would be present.

Given the possibly limited reach of the Tevatron when the lightest neutralino and chargino are nearly degenerate, it will be very important to extend these studies to the LHC. A particularly important issue is the extent to which the large $c\tau$ tails of the $\tilde{\chi}_1^\pm$ decay distributions can yield a significant rate in the background-free channels studied here. Hopefully, as a result of the very high event rates and boosted kinematics expected at the LHC, the background-free channels will remain viable for significantly larger $\Delta m_{\tilde{\chi}_1}$ and $m_{\tilde{\chi}_1^\pm}$ values than those to which one has sensitivity at the Tevatron. In this regard, a particularly important issue for maximizing the mass reach of these channels will be the extent to which tracks in the silicon vertex detector and/or in the central tracker can be used for triggering in a high-luminosity environment.

While finalizing the details of this study, another paper [20] appeared on the same topic. Some of the signatures discussed here are also considered in that paper. Our studies are performed at the particle level and contain the most important experimental details.

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References

- [1] H. Baer, K. Cheung and J. Gunion, *Report on the gluino-LSP scenario*, to appear in “Proceedings of the Tevatron SUSY/Higgs RunII Workshop”, eds. M. Carena and J. Lykken (AIP).
- [2] A. Brignole, L.E. Ibanez, and C. Munoz, *Nucl. Phys.* **B422** (1994) 125, Erratum, *ibid.*, **B436** (1995) 747; hep-ph/9707209.
- [3] C.H. Chen, M. Drees, and J.F. Gunion, *Phys. Rev. Lett.* **76** (1996) 2002.
- [4] C.H. Chen, M. Drees, and J.F. Gunion, *Phys. Rev.* **D55** (1997) 330.
- [5] C.H. Chen, M. Drees, and J.F. Gunion, hep-ph/9902309.
- [6] G.F. Giudice, M.A. Luty, H. Murayama and R. Rattazzi, *JHEP* **12** (1998) 027.
- [7] L. Randall and R. Sundrum, hep-th/9810155.
- [8] G. Anderson, C.H. Chen, J.F. Gunion, J. Lykken, T. Moroi and Y. Yamada, hep-ph/9609457, published in *New Directions for High Energy Physics*, Proceedings of the Snowmass96 Summer Study, June 25 – July 12, 1996, Snowmass CO, eds. D.G. Cassel, L.T. Gennari, and R.H. Siemann, p. 669.
- [9] J.F. Gunion and H.E. Haber, *Phys. Rev.* **D37** (1988) 2515.
- [10] S. Thomas and J.D. Wells, *Phys. Rev. Lett.* **81** (1998) 34.
- [11] S. Mizuta, D. Ng, and M. Yamaguchi, *Phys. Lett.* **B300** (1993) 96. A. Papadopoulos and D. Pierce, *Nucl. Phys.* **B430** (1994) 278. D. Pierce, J. Bagger, K. Matchev, and R.-J. Zhang, *Nucl. Phys.* **B491** (1997) 3.

- [12] The CDF II Collaboration proposal for Enhancement of the CDF II Detector: An Inner Silicon Layer and A Time of Flight Detector, Fermilab-Proposal-909.
- [13] G. Landsberg (DØ Collaboration), private communication; D. Cutts and G. Landsberg, hep-ph/9904396.
- [14] D. Stuart (CDF Collaboration), private communication.
- [15] P. Abreu *et al.*[DELPHI Collaboration], CERN-EP/99-37. See also, S. Paiano, A. Perrotta, T. Rovelli, R. Alemany, and C. Garcia, DELPHI 98-74 CONF 142, June 1998, to appear in the Proceedings of the 1998 International Conference on High Energy Physics, 23–28 July, 1998, Vancouver, BC, Canada.
- [16] T. Sjostrand, Comput. Phys. Commun. **82** (1994) 74; S. Mrenna, Comput. Phys. Commun. **101** (1997) 232.
- [17] F.E. Paige, S.D. Protopescu, H. Baer and X. Tata, hep-ph/9810440.
- [18] K.T. Matchev and D.M. Pierce, hep-ph/9904282.
- [19] From the transparencies of the talk by Rick Field at the CDF QCD subgroup Meeting, January 14, 1999, available at http://www.phys.ufl.edu/~rfield/cdf/rdf_cdf.html.
- [20] J.L. Feng, T. Moroi, L. Randall, M. Strassler and S. Su, hep-ph/9904250.